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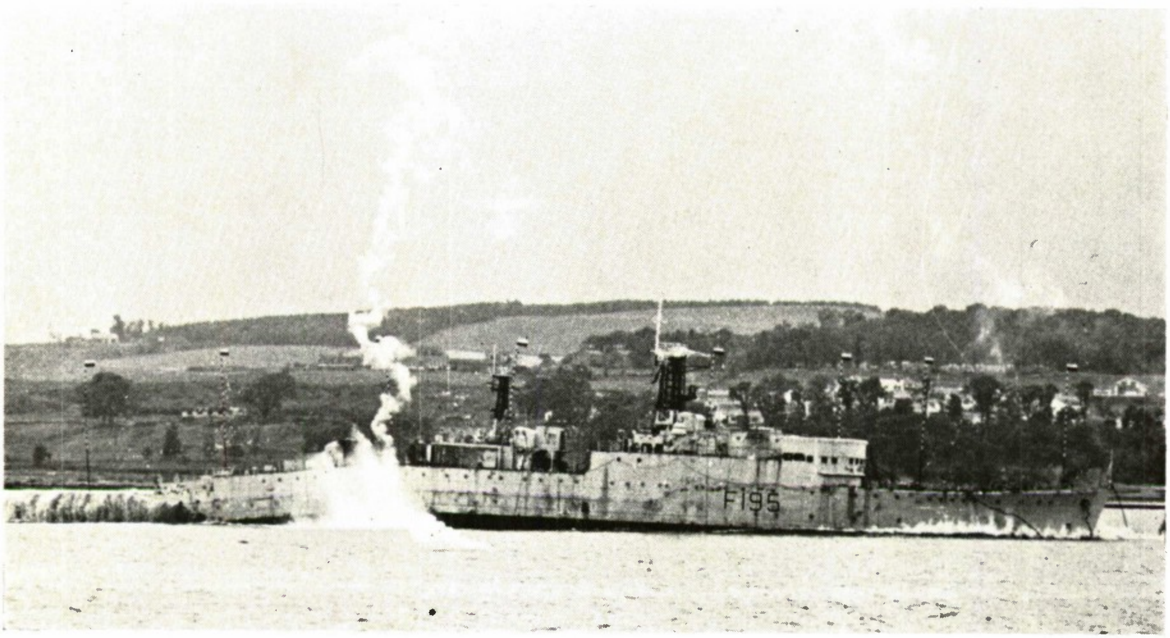

H.M.S. " Roebuck " and H.M.S. " Broadsword " are being used by the Naval Construction Research Establishment for trials this summer as part of an investigation on the effectiveness of underwater explosions. The photograph shows the " Roebuck " at the instant of maximum " jack-knifing " abreast the charge (approximately 8°). The ships have been extensively instrumented to measure displacement, velocity, acceleration and strain and are beached after each test to inspect the structural damage. The tests form part of a U.S./U.K. co-operative programme of explosive research, the Americans having already conducted tests against two of the ships earlier this year.

QUAVER—A NEW CONCEPT IN AUTOMATIC VOLTAGE CONTROL

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SUMMARY

A new system of automatic voltage control for a.c. generators, which is unconditionally stable, and has a response time to load changes greatly superior to any automatic voltage regulator at present available, has been developed. Any type or size of a.c. generator can be controlled by this system, but it is particularly suitable for brushless machines. All the following material is derived from development work and tests carried out in the Electrical Department of the Admiralty Engineering Laboratory at West Drayton, Middlesex. Further development work is being undertaken which should result in an early application of this system in the Fleet. The name "Quaver" is derived from QUick Acting VoltagE Regulator.

Historical Survey

In 1831 Michael Faraday discovered how mechanical energy could be converted into electrical energy through the medium of a permanent magnet being moved in and out of a coil of wire. Attempts were then made to produce a useful practical machine using this principle. The solution to this problem was not possible as long as the necessary magnetic flux was obtained by the use of permanent magnets, since these were neither permanent nor powerful enough at this time. Several investigators worked on this problem, notably Wheatstone, Varley, and Werner Siemens. In 1866 Siemens[1] was inspired to eliminate the use of the bulky permanent magnets by substituting an electro-magnet system. Shortly afterwards the firm of Siemens began the manufacture of what was called the dynamo-electric apparatus, the first machine for generating electrical energy in useful amounts. These early machines were used mainly for lighting, using carbon arc lamps. The first incandescent lamp, a carbon filament type, was successfully demonstrated some 12 years later on the 18th December, 1878, by Swan. This work was of course paralleled by Edison and announced almost simultaneously.

In 1885 the Admiralty arranged for H.M.S. *Inflexible*[2] to be the first British naval vessel to be fitted with electric lighting. The dynamo employed had the following specification. Dynamo, Compound Wound, SELF REGULATING, normal load at 400 revolutions, 250 Incandescent

lamps of 20 candlepower, E.M.F. 80 volts commutator insulated between segments with mica. One of these early machines from H.M.S. *Inflexible* is now preserved at the Admiralty Engineering Laboratory in the entrance hall of the Electrical Office Block. The early incandescent lamps used were electrically fragile inasmuch as over-running caused volatization of the carbon filament with a preferential attack on the negative end. Thus the need to regulate the generator output, so that the voltage remained constant at all values of loading on the generator, was early recognized and allowed for in the design of the generator.

As might be expected at this time, from the experience of electrical engineers with the power sources then available, which of course were all direct current sources such as primary and secondary cells, direct current machines were mainly employed. Alternating current sources were not easily understood or utilized. Circa 1890, the Mordey Alternator, with a single phase output and employing a direct current exciter, was produced. At the Frankfurt Exhibition of 1891, great interest was aroused by the demonstration of multiphase operation and the use of multiphase alternating current for driving electric motors. Up to this time all alternating current motors were of necessity single phase and were very poor competitors to the direct current motor. From this development stemmed the fantastic growth in electrical power generation and utilization. Spectacular progress was simultaneously being made with steam engines and steam turbines, diesel engines, and petrol engines. Thus as electrical engineers discovered how to make electrical generators with larger and still larger outputs, mechanical engineers provided the necessary prime movers with sufficient output to drive the new machines.

For marine purposes, direct current working was preferable for many years. One of the main reasons was the simplicity of direct current control of motors compared to alternating current control. As ships' generating capacities grew with the ever-increasing use of electrical equipment, this situation gradually changed until the advantages of using alternating current supplies were indisputable.

Continued development of electrical supplies depended for a very long period of time on the generator designer alone, the increased electrical performance demanded being met by improved design in the electrical characteristics of the generator. Many improvements were evolved until machine design was almost completely standardized. Accurate regulation of voltage was the main requirement from users, another being good transient response, *i.e.* the ability of the generator to respond rapidly to new load conditions. With the development and use of the larger motors, sudden large loads could be applied to the supply system and cause difficulties to the users of more sophisticated equipment, who then insisted on their own individual supplies from a separate machine or were compelled to fit expensive regulating circuits in the equipment itself.

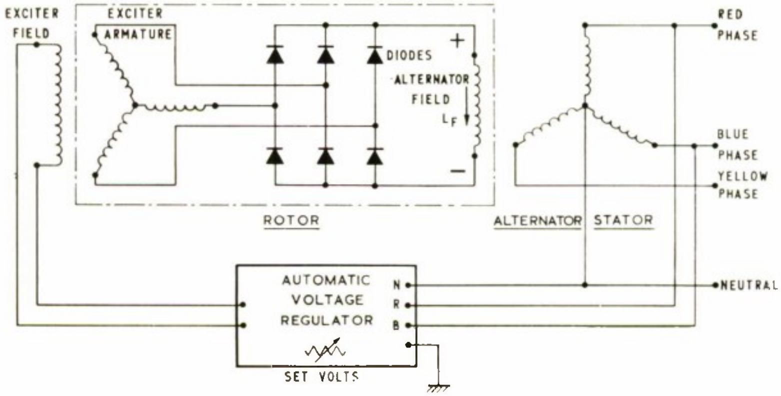


FIG. 1. Typical Brushless Machine with A.V.R.

In general the output voltage of any generator depends upon the strength of the magnetic flux linking with the generating conductors, and this in turn depends on the strength of the energizing current flowing in the electro-magnetic system producing the magnetic flux. To maintain a given output voltage, over a wide range of loading, all that is necessary is to alter the current in the winding generating the magnetic flux; increasing the current increases the output voltage, decreasing the current decreases the output voltage. This problem was readily resolved in the early days by fitting a voltmeter to the output terminals of the generator, a suitable variable resistance in the field circuit, and closing the control loop with a suitable employee. This method, incidentally, was still in use for a certain application at A.E.L. until as recently as 1966. Old customs die hard ! The transient response was not particularly rapid. An automatic method of control was required, and over the years a bewildering variety of voltage regulating devices were devized such as vibrating relays, carbon pile regulators, valve circuits, thyratron circuits, magnetic amplifiers, and so on until the advent of solid state devices. These devices opened up a totally new prospect of controlling electrical generators. One of the first applications was that of employing rectifying diodes in a circuit arrangement such as shown in Fig. 1. Machines employing this arrangement are termed " brushless " machines since no electrical energy is fed to or from any rotating component via brushes, sliprings or commutators. Regulation is effected by an external voltage regulating circuit and can be as good as the available money allows. The transient response leaves much to be desired from a naval point of view and furthermore is decidedly asymmetrical. When a load is suddenly applied to the output of a brushless machine, the voltage is rapidly restored to the original value; removal of the load results in an increased output voltage which persists for a much longer period until the field current returns to its steady state value. This effect is caused by the current in the field circuit being maintained by the highly inductive field winding, through the diode bridge, until the field circuit losses allow the current to fall to the required value. This phenomenon is known colloquially as " flywheeling " *i.e.* the current " flywheels " via the diode bridge.

Since brushless machines possess overwhelming advantage from a maintenance point of view, with the elimination of all the wearing parts other than rotor bearings, a solution to the transient response was highly desirable, and this represented the starting point of the R and D programme which forms the major part of this article. At this time another solid state device was emerging that appeared to have great possibilities for control work; this device was called the silicon controlled rectifier or, as is more common to-day, the thyristor. Many new schemes were put forward but, although useful for commercial purposes, did not meet the more stringent requirements of the Navy.

The main weakness in all the preceding systems was a fundamental one caused by electrical engineers persisting in searching for a solution along the same lines, merely using the same basic configuration with new devices. Each solution in turn, with few exceptions, used the controlling circuit to control the field current of the exciter and this in turn controlled the field current of the generator. This method has the advantage that the exciter is used as a power amplifier but two serious disadvantages also result. One is that there are two major inductive loops in the overall regulating circuit, which may cause instability under certain operating conditions. Another is the inability to drive the generator field current down rapidly when required to reduce the output volts, causing a delay in response, due to the flywheel effect previously mentioned.

As is often the case in development work, two completely parallel paths of applied research were being pursued that were to lead to a solution of the problem that had baffled electrical engineers for a long time. One path was being explored at A.E.L.(L) by Captain Craddock (R.N. Rtd.) who, early in 1964, devized the correct basis for applying thyristors to control electrical generators in order to obtain fast response times to transient conditions, of an order better than previous controlling schemes. Unknown to him, the Societe Generale de Constructions Electriques et Mechaniques (Alsthom), in France, had already filed a specification which described a closely similar control system[3]. However, as far as is known, the initial feasibility study of Captain Craddock, and the work of the team led by him, which was later assigned to develop the scheme, resulted in the first resolving of the practical details necessitated by the improved method of control. Captain Craddock was an early investigator into the use of silicon controlled rectifiers at A.S.W.E., his attention then being directed principally towards the control of a.c. motors; on joining the Admiralty Engineering Laboratory his duties directed his attention to the possibility of using these devices for generator control and, by examining the basic problem from a completely fresh viewpoint. He evolved an improved system.[4] The practical realization of this system took some time because of the many problems that subsequently appeared; the more important of these will be discussed later.

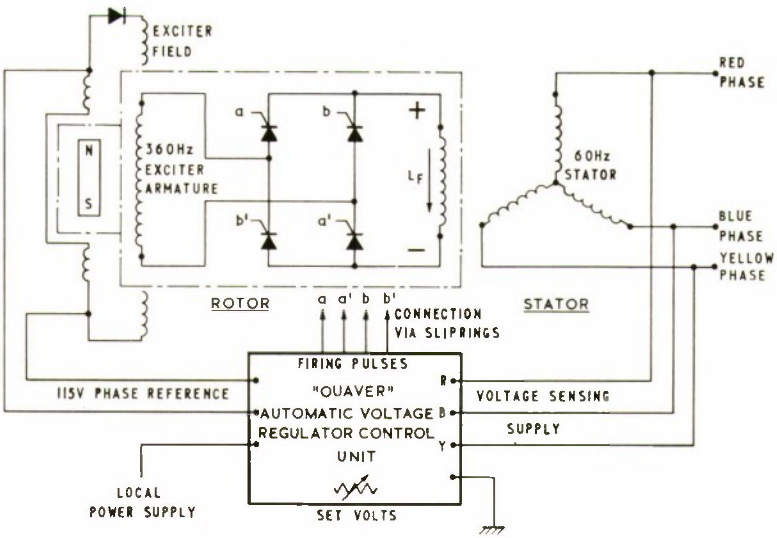


FIG. 2. First Basic QUAVER Automatic Voltage Regulator.

QUAVER

The original system, to which the name *QUAVER* was given, is shown in Fig. 2. It utilized a single phase exciter and a full wave thyristor bridge controlling the output of the exciter. Transfer of control to this point results in a dramatic improvement in transient response. An auxiliary phase reference generator is necessary to provide phase reference voltages to the control circuits, but the power required is so low that a permanent magnet generator may be used.

Basic QUAVER Control Action

The basis of control by *QUAVER* is by the use of silicon controlled rectifiers or thyristors. For those unaware of the mysteries of science contained in these devices[5], it is sufficient to regard a thyristor as a normal power diode that can be switched on, as required, by a voltage to the thyristor gate. Once switched on, the thyristor cannot be turned off again until the current falls below a critical value known as the holding current. The thyristor then ceases to conduct and, after a very brief period of time assumes a state of high resistance. For those more familiar with valves, the thyristor is the solid state analogue of the thyratron valve. During the conduction period the resistance of the thyristor falls to a very low value and even for very large currents the voltage drop in the device is only about one volt.

In the following discussion of the action of the thyristor bridge when driving an highly inductive load such as the main field of a generator L_f, it is assumed, as indeed occurs in practice, that *forward current flows continuously in the main field circuit*. Reference to Fig. 3 will assist in understanding the basic action of the *QUAVER* control, in this case for a single phase exciter, this being much more easy to describe and understand than the action of a three phase thyristor bridge. Fig. 3 shows the voltage across the main field under various conditions of generator loading. Under steady state conditions as in Fig. 3a, thyristors aa′ are fired and the voltage across the field is shown by the heavy line; 180° (electrical) later, thyristors bb′ are fired and, since forward volts are across these, take over the field current from aa′ which then turn off. Due to the reversing action of the bridge, the field has imposed upon it the same voltage waveform from bb′ as from aa′. The difference in the areas above and below the voltage zero cause a mean voltage in the forward direction to be applied to the field, sufficient to maintain the field current at the correct mean value, the power absorbed being the I^2R losses in the field winding. When a sudden extra load is applied to the generator the error sensing circuit causes the firing points of the thyristors aa′ and bb′ to be advanced as shown in Fig. 3b, with the indicated voltage waveform, an increase of mean voltage applied to the field and hence a rapid increase of field current. This is known as "Forcing UP" and if the firing points of aa′ and bb′ are advanced to 0°, full forcing occurs and is limited only by the characteristics of the exciter. A few tens of milliseconds after the load has been applied, the system reverts to the condition of Fig. 3a, with an almost imperceptible advance of the firing points to give the new field current required for normal output

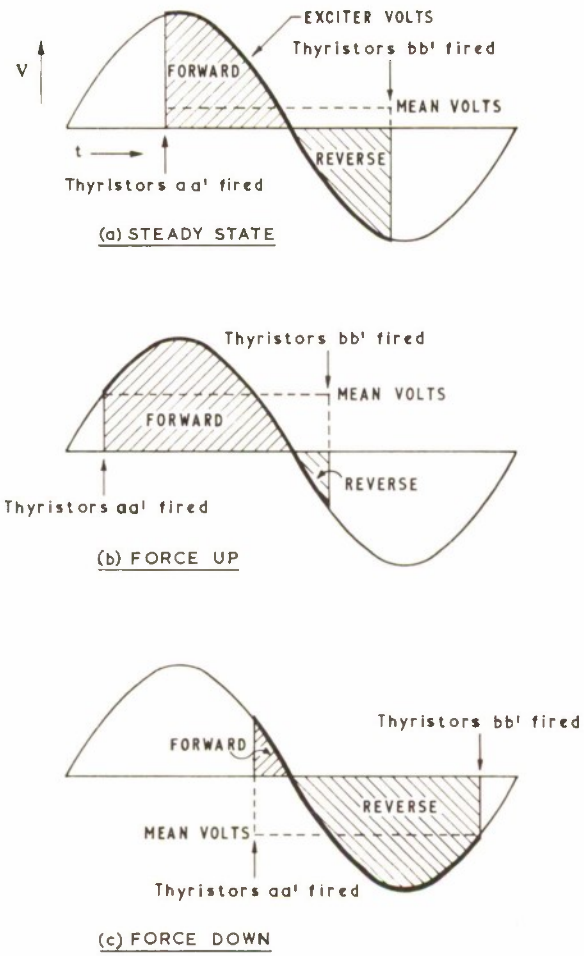


FIG. 3. QUAVER Action—Single Phase System.

voltage across the increased load. Should a load be suddenly removed, the firing points of the thyristors aa′ and bb′ are retarded as shown in Fig. 3c, the voltage waveform alters as shown, and the mean voltage applied to the field is *reversed*, and the field current is rapidly reduced. This is known as "Forcing DOWN", and again the maximum forcing down at full retardation of the firing points depends upon the characteristics of the exciter. In this case inversion is taking place *i.e.* energy is being removed from the main field circuit *but* the field current is *never reversed*. Inversion takes place for a very short period of time as only sufficient electrical energy is removed from the field to bring the field current down to the new value to give the required output voltage across the new load. A few tens of milliseconds after the removal of the load the system reverts to the conditions of Fig. 3a. One interesting result is that it is possible to force the generator main field current down more rapidly than upwards, since the ordinary field losses assist this action. Normal regulation, such as is required for small load changes, and slow changes of load, requires only a very limited change in pulse firing position and indeed is scarcely detectable from no load to full load, once the transient changes have ceased. Lack of space prohibits a description of the electronic circuits used to control the firing point position of the thyristors in the first *QUAVER* arrangement shown in Fig. 2, but the principle of operation is basically that of the A.E.L. prototype *QUAVER* control unit about to be described.

Description of Operation of A.E.L. QUAVER Control Unit

The A.E.L. prototype *QUAVER* control unit consists of six identical control channels. It is designed for use with a three-phase controlled bridge and the block diagram of the interconnections between the unit and the controlled generator is shown in Fig. 4. The actual control unit is shown in Fig. 5. Each channel consists of a ramp and limit-pulse generator, controlling a Schmitt trigger circuit whose output is inverted and fed into a monostable which generates a pulse of 50 microseconds duration. This pulse is fed to the base of a switching type transistor, through a Darlington pair emitter follower stage in order to obtain sufficient drive to ensure that the output transistor is fully switched on for the duration of the pulse. Although the mean dissipation in the output transistors is so small that a heat sink is unnecessary, the maximum current at the end of a 50 microsecond pulse is 8 amperes. A diode ring circuit on the invertor output also simultaneously directs an input to another monostable in another channel so that an output pulse is simultaneously generated in that channel feeding the thyristor which also has to conduct in order to complete the appropriate bridge arm at a particular instant. In order that the output transistors will switch on rapidly and give a fast rise time to the output pulse leading edge, and also to damp out ringing oscillations in the long cable connection to the pulse transformer, a ten ohm resistor and a silicon diode in parallel are shunted across the primary connections at the control unit end. It would theoretically be better to have these components at the pulse transformer end but in practice the results are almost the same and an endeavour has been made to keep all the "electronics" in the control unit as far as possible. The diode plays an important part in preventing inter-channel interference being transmitted through the pulse transformer, by allowing the primary current to flywheel down to a low value at the end of the output pulse. (This is a good example of an unwanted effect in one part of the system being put to good use elsewhere.)

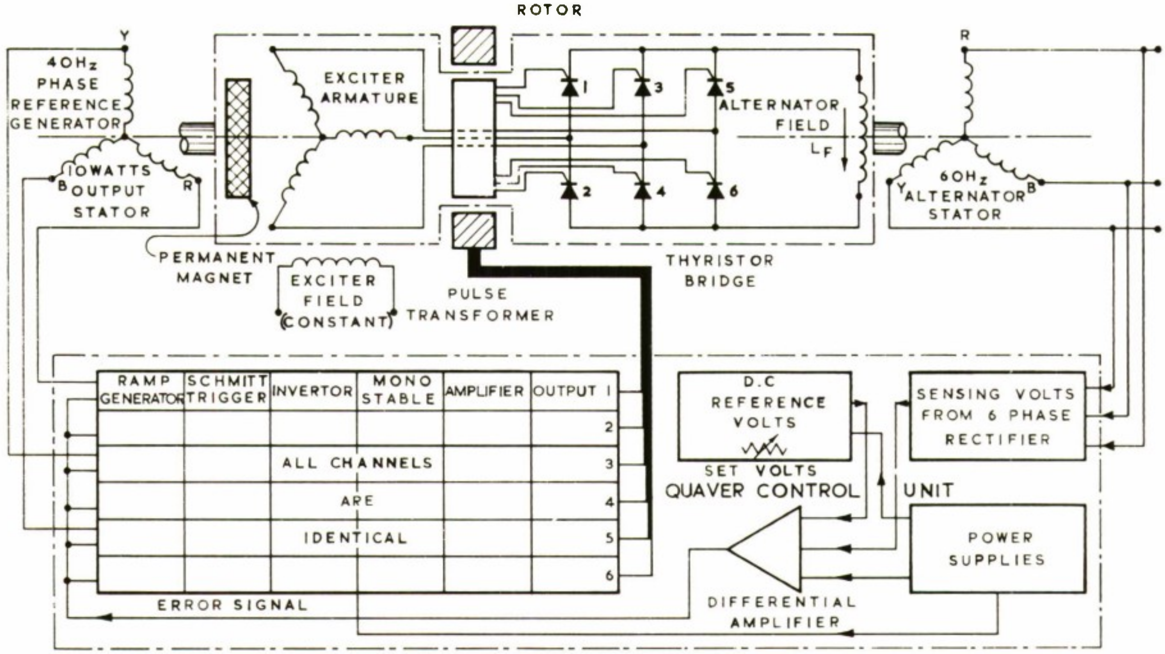


FIG. 4. A.E.L. Prototype QUAVER Control System.

The rate of change of primary current is then made insufficient to cause interaction with another channel through the ferrite core of the transformer; the importance of this will be seen when the pulse transformer is discussed later. The ferrite core chosen has a very limited response to low frequency current changes but is very efficient at higher frequencies. When the induced voltage across the primary reduces to the extent that the diode can conduct no further, at about 0·8 volt, the 10 ohm resistor prevents a sudden cessation of primary current and dissipates the remaining energy so that the ferrite core is re-set in readiness for the next output pulse. An output pulse of 24 volts magnitude and with a peak current of six amperes is readily generated, with a fast rise time and little overshoot of the trailing edge.

Phasing of the firing pulses results from the action of the Schmitt triggers whose inputs are fed from the sinusoidal ramp for phase reference purposes. In addition a d.c. error signal is derived from the a.c. generator output via a six phase full wave rectifier output and a d.c. reference voltage, and the difference is passed through a high performance differential amplifier and fed to the input of the Schmitt triggers. Thus the precise instant of triggering of the Schmitt triggers is dictated by the sum of the ramp voltage and the d.c. error voltage. The output from the differential amplifier is sufficient to cover 180° of the sinusoidal ramp from its minimum to its maximum excursion. In other words, the d.c. error voltage forces the sinusoidal ramp up and down as required, and this determines the precise instant at which the Schmitt trigger will fire and hence the precise phasing of the generated firing pulse. The normal operating point of the ramp, under steady state conditions of the system, is almost at the mid-point position. When the Schmitt trigger fires, the resulting square wave output passes through the invertor, merely

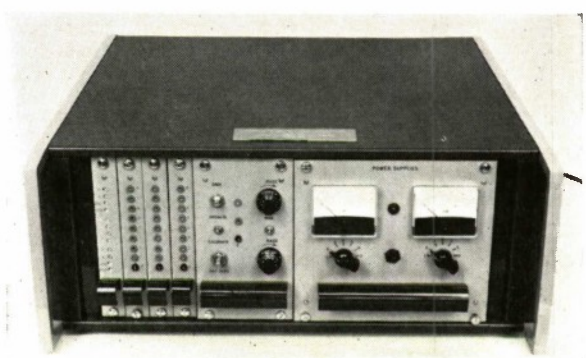


FIG. 5. A.E.L. Prototype QUAVER Control Unit.

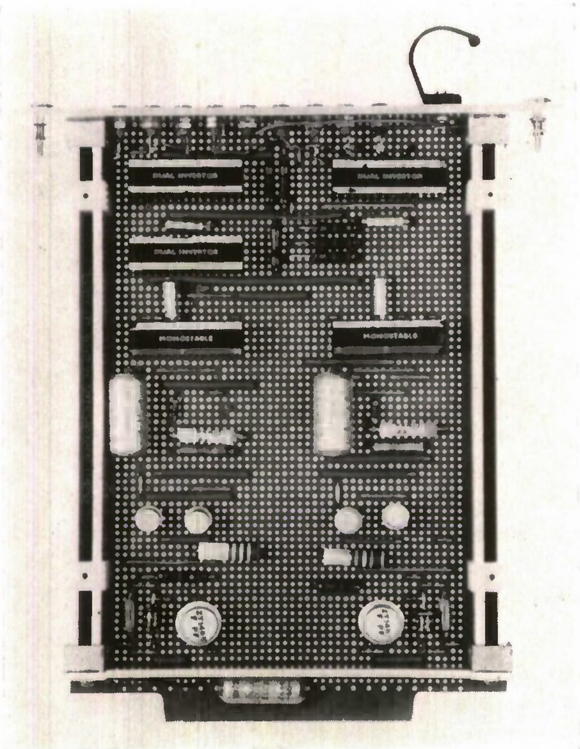


FIG. 6. Two Channel Firing Pulse Phase Control Unit.

for reversal of sense, and the invertor output pulse triggers its own monostable and, simultaneously, through the diode ring circuit, its complementary monostable. Thus two output pulses, from the appropriate channels, at the correct phasing for the load on the main generator, are delivered to the correct pair of thyristors in the three-phase bridge. As the error voltage signal response is almost instantaneous, due to the very short time constant of the filter in the sensing and error signal circuits, corrective phase shifting of the firing pulses occurs at a frequency of six times the frequency of the phase reference supply; *i.e.* in the case of a 40 Hz phase reference supply, at 240 times a second or approximately every 4 milliseconds. This fast response, and the use of a 12 pulse rectifier circuit for the sensing voltage, results in any ripple voltage on the output error voltage from the differential amplifier having practically no effect on the controlling action; this is a great help in reducing the time constant of the filter used to an absolute minimum. A protective limit pulse is provided at each end of the sinusoidal ramp to maintain firing pulses to the thyristors at the maximum phase displacement of 90°; this avoids the remote possibility that over-driving of the ramp, with the possible loss of control of the thyristor bridge, can take place. Other refinements in the circuits are provided but these will not be described. A major part of the prototype control unit shown in Fig. 5 consists of power supplies which are quite conventional. Since the basic operation in the control circuits is that of switching, use was made of Ferranti integrated circuit blocks, with added discrete components, mounted on Veroboard and fitted with plugs for ease of removal when necessary. Fig. 6 shows a typical phase control unit with two channels for one exciter phase control.

As the control unit may be situated some distance from the controlled generator, a screened cable containing three cores is used to conduct the three-phase reference ramp supplies. No interference voltages must be present on this input or adverse performance will result. Output pulses from the control unit are conducted along an overall screened cable containing seven individually twisted pairs of conductors, each twisted pair giving electrical isolation to one output pulse channel, with a spare pair for monitoring purposes. The remote end of the output cable is connected to the pulse transformer, shown in Fig. 10, through a junction box. This transformer is mounted on the shaft of the controlled generator and a description of the development of this unit is now appropriate.

Development of Rotating Pulse Transformer

The first application of the *QUAVER* automatic voltage regulator system to a 250 kW Brushless machine, utilized sliprings and brushes to conduct the firing pulses to the thyristor gates. This was necessary as the preferred inductive coupling method had not then been developed, although several promising approaches had been devised. The slipring unit can be seen at the very end of the 250 kW Brushless machine shown in Fig. 7, which also gives a clear view of the thyristor bridge, mounted on a circular disc, with the protective fuses nearby. See also Fig. 8. Sliprings were of course a retrograde step but at this stage it was necessary to demonstrate the effectiveness of the *QUAVER* control system on a typical brushless machine. There are many disadvantages in the use of sliprings in a thyristor gate circuit *e.g.* inherent electrical noise voltages and leakage currents, either of which can trigger a sensitive thyristor gate, and much trouble was experienced using this method, in spite of the fact that the slipring unit used was of a special type to alleviate the known disadvantages. Once the *QUAVER* control system had been clearly demonstrated to be completely adequate on a typical brushless machine, development proceeded to produce a suitable firing pulse coupling method to replace the sliprings.

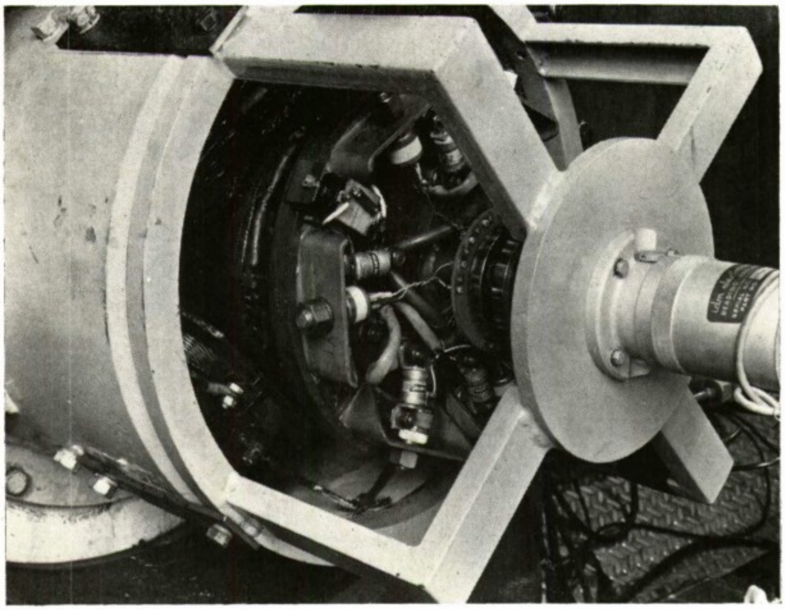


FIG. 7. Thyristor Ring in 250 kW Brushless Machine.

A fully controlled three-phase bridge requires at least six firing pulses and the *QUAVER* control unit already described actually uses six pairs of firing pulses. The original *QUAVER* control unit shown in Fig. 8 mounted on a trolley, used a short train of pulses, about 20 pulses in a train, each pulse being 10 microseconds in width, at a pulse repetition frequency of approximately 10 - 15 kHz, for each thyristor gate. The philosophy was that if the initial pulse of the train did not fire the thyristor gate, sooner or later one of the train of pulses must do so. At the same time the dissipation at the thyristor gate was not as great as if a single wide pulse was used. The excellence of this mode of operation is demonstrated by the fact that during the development programme five machines of widely varying characteristics and output capacities were controlled with the utmost ease. Difficulties in the use of trains of pulses became apparent later on, and led to the abandonment of this method.

Attention was therefore focused on the type of coupling required to conduct the thyristor gate firing pulses. There are several possible alternative methods *e.g.* capacitive coupling, solid state lamps and photo-diodes or photo-transistors, inductive coupling, radio frequency coupling, *etc.*, the main requirement being the transmission of the firing pulses from a stationary electrical component to a rotating electrical component mounted on the shaft of the generator, without physical contact and without change in transfer characteristics with rotation. Ultimately it was decided to concentrate on the inductive coupling method as having the most promise and offering the least complexity. The problem was approached by considering the action of an ordinary iron cored transformer and splitting the magnetic circuit so that a small air gap existed between the primary and secondary magnetic material. To allow for 360° rotation between primary and secondary windings, a unit was built up from standard E transformer laminations. Fig. 9a shows the primary half of one such unit, and Fig. 9b the development of this which gave satisfactory results. This was difficult to manufacture and would have resulted in a very expensive pulse transformer. Other ferro-magnetic materials were obtained in the form of rings including annuli of wound strip. An example is shown in Fig. 9c. These were not successful and attention was directed to the use of Ferroxcube Toroids—a manganese zinc ferrite Type 4[6]. Although this material seemed to possess suitable magnetic properties, it also proved to be exceedingly hard and brittle. The hardness is approximately 8 - 9 on the Mohs scale and this material can only be cut by the harder materials such as corundum, aluminium oxide, and diamond. As only solid annuli for toroidal windings were available, the immediate problem was how to cut them and form grooves for the purpose of holding the necessary windings. An outside firm thought that the problem could be solved; six pairs of rings were

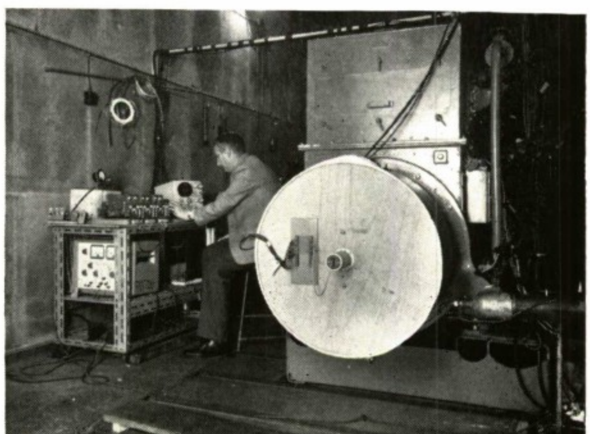
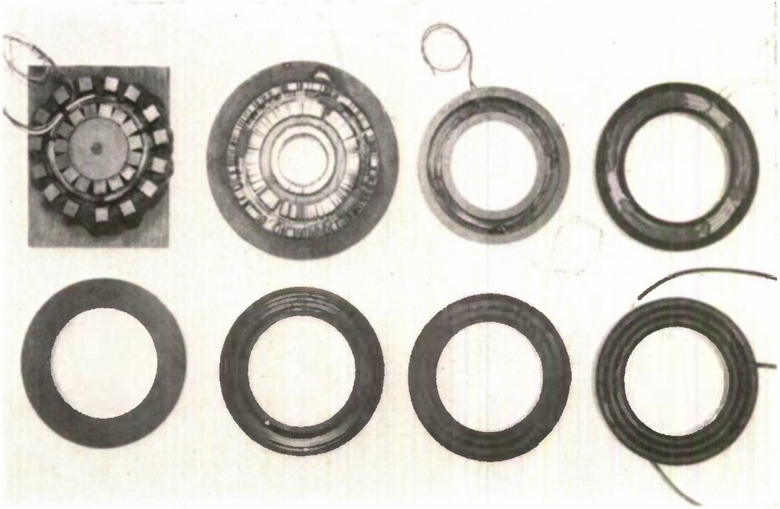


FIG. 8. Load Testing of 250 kW Brushless Generator.

FIG. 9. Development of Rotating Pulse Transformer.

a b c d

e f g h



taken away and, six months later one pair of rings returned; the others, alas, had perished and so had a number of cutting tools ! This type is shown in Fig. 9d. Meanwhile an alternative method of cutting the rings was sought. Tests were conducted using an ultrasonic generator driving a cutting tool and which which ultimately proved successful. The actual cutting is performed by a mild steel tool, ultrasonically vibrated, with a cutting medium of a silicon-carbide-and-water slurry.

Tests showed that a pair of single channel ferrite rings was adequate for the transmission of firing pulses, and attempts were made to utilize each pair of rings for two channels and thus reduce the final number of rings required. After partial success with this mode of operation, thoughts were turned to the possibility of utilizing each ring for three channels and finally the rings were cut with three grooves approximately one eighth of an inch wide and three sixteenths of an inch deep, as shown in Figs. 9e - h which illustrate the original ring blank; the two grooved ring, the three grooved ring as cut by a diamond tool, and the final transformer component using an ultrasonically cut three grooved ring complete with three windings embedded in epoxy putty. The windings chosen were largely dictated by the very limited space of the grooves and the type of insulated wire available for the secondary windings, these windings having to be capable of withstanding the full voltage of the exciter. Ferrite has reasonable insulating properties and this eased the problem. Electrical and mechanical considerations dictated the use of a p.t.f.e. insulated wire for the secondary windings, which would only allow the housing of six turns of wire in each groove. The magnitude and duration of the firing pulse at the thyristor gate was calculated to be 6 - 8 volts and 50 microseconds to be certain of firing the thyristor under all conditions likely to be encountered. The firing pulse has to pass through a protective circuit containing a current limiting resistor and two silicon diodes in series, with a resistor shunting the thyristor gate; a voltage of at least 10 - 12 volts was therefore necessary on the secondary side to achieve this value. Experiment showed that a minimum of 12 turns was necessary on the primary side to obtain a pulse width of 50 microseconds and hence the two-to-one stepdown ratio meant that a primary pulse of 24 volts magnitude was necessary. At this stage it was very heartening to find that when such an arrangement was tested, separation of the primary and secondary assemblies did not seriously affect the magnitude of the transmitted pulses over a gap range of 0·005 - 0·025 in.

In order to minimize the interference between channels, the middle winding of each assembly was reversed electrically, so that any induced interfering signal in an adjacent channel would be reversed in phase by 180° and be prevented from reaching the thyristor gates of adjacent channels by their protective diodes. Any residual interference getting through would be of the wrong polarity to fire the thyristors in any case. The elimination of adjacent-channel interference proved to be a most difficult problem to solve and eventually led to the abandonment of the pulse train method of firing, principally for the duration of time required for the flux re-set of the ferrite core, following the increase in pulse width to 50 microseconds, which limited the pulse repetition rate to a maximum of 2 - 3 kHz. Any speeding up of the flux re-set time to obtain a higher repetition

rate resulted in severe interference in other channels and as this could not be tolerated, the pulse train method was abandoned, although not without some regret. Other difficulties were the synchronizing of pulses and the excessive dissipation in the output transistors driving the pulse transformer. It was decided to investigate the use of single pulse working and the supplying of two synchronized pulses to each pair of thyristors required to conduct at any particular instant. Cross connection of the firing circuits, by a diode ring input to the monostable units, was found to be eminently suitable to produce the synchronized leading edges of the pair of firing pulses. Excellent output pulses from the secondaries, of 6 - 8 volts magnitude and 50 microseconds width, were obtained with the interference between channels almost undetectable. The thickness of the ferrite walls separating the grooves was also found to influence the level of crosstalk and, as can be seen from Fig. 9h, the two walls enclosing the middle winding are somewhat thicker than the other two walls at the inner and outer diameters of the ferrite ring; this is a matter of compromise and arrived at by trial and error, mostly error! It was also found that some loss occured when two adjacent channels were fired simultaneously, but this effect had little disadvantage in practice, the loss of voltage being only of the order of 0·5 - 1·0 volt.

It may be remarked at this point that the design of the pulse transformer would probably have been greatly eased if rings of a slightly larger size could have been obtained, but the manufacturers were not able to supply these because of limitations in the manufacturing process. They did however, at considerable trouble to themselves, produce moulded grooved rings which reduced the cutting process time. Another firm also produced grooved rings using diamond cutting tools but this process is not an unqualified success as the stresses set up in the cutting process crack the thin walls of the grooves.

Having succeeded in obtaining correct transfer of the firing pulses through the inductive coupling of the pulse transformer components, a static model of the rotating pulse transformer, and the associated electronic circuits for feeding the thyristor gates, was made. A breadboard control unit, single pulse working, was connected, via the simulated rotating pulse transformer, to a three-phase thyristor bridge with an inductive load representing a generator main field circuit. Two layers of kraft paper six thousandths of an inch thick separated each pair of rings. The system proved to be completely successful, turning the rings had no effect whatever on the pulses, and what was most gratifying was that, even with an axial separation of up to one inch between the rings, the firing pulses continued to control the appropriate thyristor gates and full control of the bridge was possible. Following this success, the control unit and static transformer were used to control a 350 kW machine.

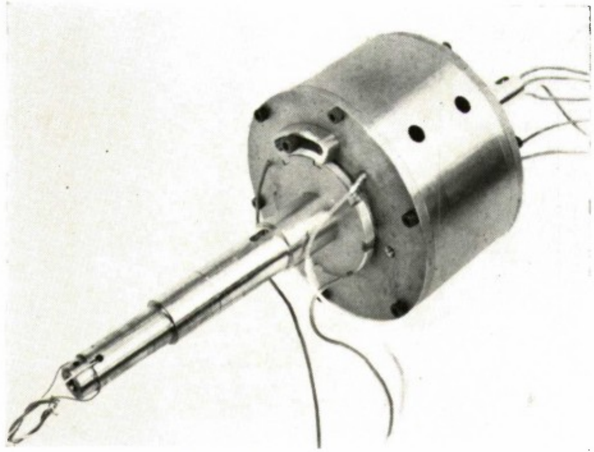
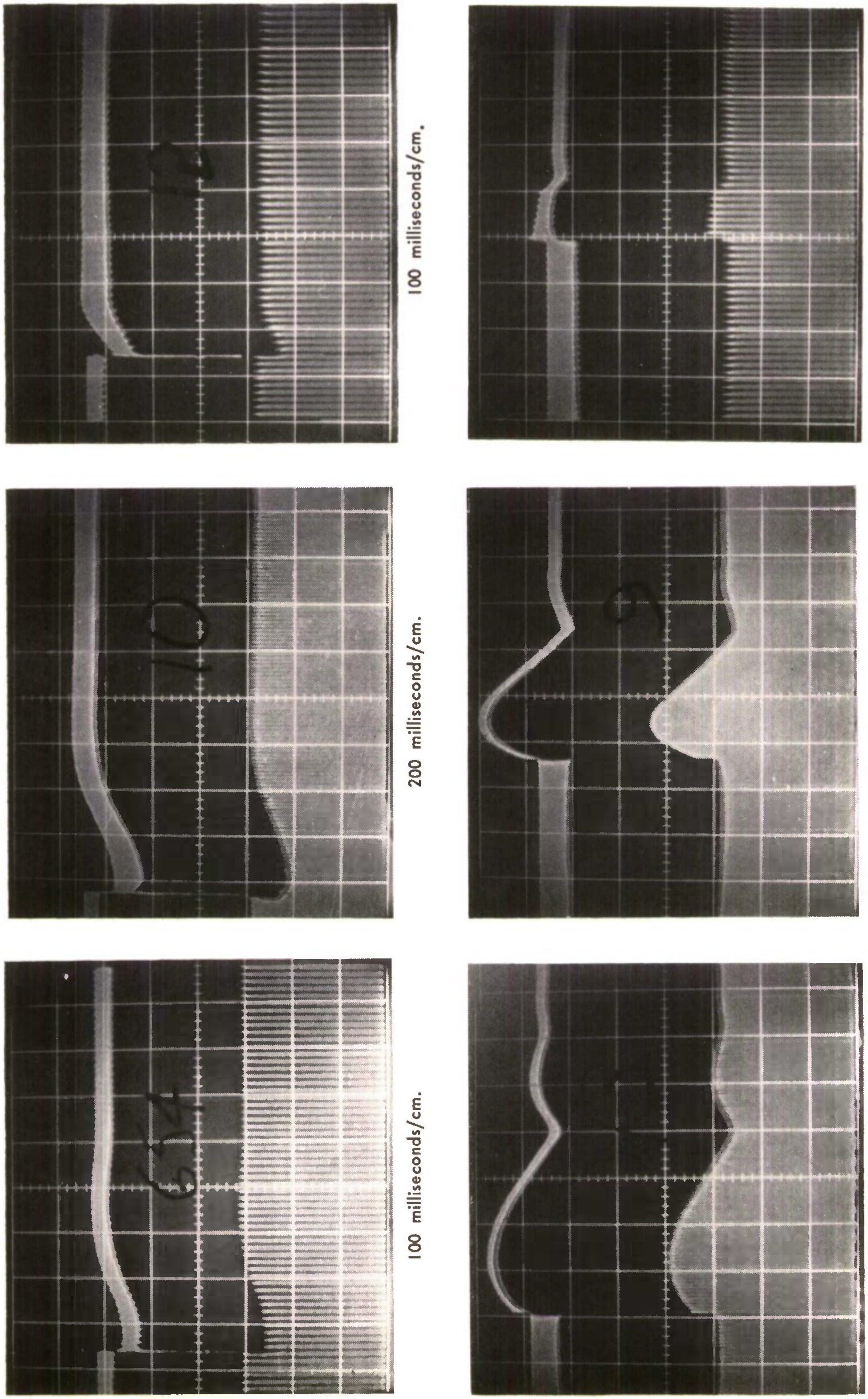


FIG. 10. Rotating Pulse Transformer—Complete Assembly.

Fig. 10 shows the rotating pulse transformer as a mechanical assembly containing two pairs of rings carrying a total of six independent thyristor firing pulse channels. Without going too deeply into the mechanical details of construction, the essential features are the two rotating rings carrying the secondary windings, mounted back to back on the revolving shaft, and paired by two facing stationary rings, carrying the primaries, mounted in the stationary outer case. The ferrite rings are secured by epoxy resin into machined steel housings to give adequate mechanical strength and magnetic isolation. Connections from the secondary windings run through the centre of the hollow shaft to the thyristor ring assembly. The primary connections are taken out of the ends of the steel casing to a junction box. A total gap of 0·024 in. is allowed for the two air gaps, by a distance piece; and the individual gap of 0·012 in. between each pair of facing rings is obtained by a micrometer adjustment and inspection ports. A compression spring maintains a 30 - 40 pound axial pre-load on the bearings so that the gaps will not be affected by backlash or wear in the bearings. These latter are sealed and lubricated for life and the mechanical loading on the bearings is such that they will outlast the useful life of the generator without the need for any attention whatsoever.



Response of a 250 kW brushless generator at full load (312kVA) 0·8 power factor with the A.V.R.s shown. The upper trace shows the error sensing volts and the lower trace the peaks of one phase voltage.

Note the different time scales. All voltage scales are identical.

FIG. 11. Load Tests—Response Curves.

Final Tests

Sufficient progress was made, in the six months following the decision to change to single pulse working, to result in the first test of the complete A.E.L. prototype *QUAVER* control unit on a 500 kW Brushless machine fitted with a rotating pulse transformer. After some initial teething troubles which caused deep despair to fall on the A.E.L. commissioning team, 28th November 1967 saw the first successful test of the completed *QUAVER* system with a brushless machine. The troubles, by the way, were caused by a couple of faults in the thyristor ring assembly and were not caused by any unforeseen difficulties in the system. A preliminary performance check showed that application and removal of FULL LOAD at unity power factor was corrected within 30 and 20 milliseconds respectively, with final load regulations of 0·5%. It was most impressive to see that continued application and removal of FULL LOAD (500 kW) did not cause the slightest perceptible tremor of the pointer of the voltmeter reading the output voltage of the generator. Fig. 11 gives the typical recovery times for application and removal of loads for the Mk. 27 A.V.R.—the best automatic voltage regulator used in the Fleet (magnetic amplifier type); an electronic automatic voltage regulator, and the *QUAVER* automatic voltage regulator. The results obtained were a most welcome conclusion to a period of considerable R and D effort. Further work continues but will be based on the commercially produced *QUAVER* control unit.

From the results achieved up to the present it appears that the *QUAVER* automatic voltage regulator may well become the standard A.V.R. for a.c. generators in the Fleet. The advantages of *QUAVER* are considerable, since it offers a transient response far better than the best of the existing conventional A.V.R.s, the system can be applied to any a.c. generator without major modifications, no critical adjustments are necessary in the control unit, the system is unconditionally stable, even with a power factor from a capacitive load as long as this is below that critical for the machine itself; with no overshoot or oscillation on the recovery from application or removal of the loads up to the full capacity of the generator. The control unit may be situated up to 50 yards from the controlled machine, almost normal operation continues even if some of the components fail, *e.g.* one of the thyristors in the three-phase bridge or one of the control channels, and not the last nor the least advantage is that ultimately the *QUAVER* automatic voltage regulator should cost less than the present generation of A.V.Rs. Fault diagnosis and repair are comparatively simple, through the use of monitoring points and plug-in modules, providing a dual-trace oscilloscope is available.

There is one minor disadvantage in that alternative supplies are necessary for test purposes if the main generator is not running since the phase reference and power supplies also cease. The power required however is very small. The determination of the *QUAVER* system to function even under adverse conditions is remarkable, and this makes it imperative to fit thyristor failure indicators since malfunctioning due to thyristor failure is not detectable without a high-speed oscilloscope or a high-speed voltage transient recorder. A thyristor failure detector circuit was developed during the development of *QUAVER* but, although effective, a simpler commercial unit[7] has been developed which will be more suitable. If a thyristor goes open circuit, or a short-circuited thyristor causes the protective fuse to blow and produces the same effect, a ripple current will be caused to flow in the exciter field by the unbalance in the exciter phases. This unbalance can be detected by means of a current transformer and a neon lamp. Should a thyristor fail, it is not necessary to shut down the generator immediately; this may be done at the next convenient time, as the system will continue to function quite successfully, the only effect being that the response time is increased somewhat, but not seriously. Incidentally, the variations of speed that may occur at the generator shaft do not affect the *QUAVER* performance at all, merely causing slight variations in the controlled field current. In fact speed variations may be seen reflected in these small variations of field current.

Future Developments

These are likely to result in simplification of the system and will probably use integrated circuits mounted on the rotor of the generator itself. Elimination of the pulse transformer is then possible but the new problem will be the transfer of the sensing voltages and power supplies to the circuits on the rotating shaft, although this involves low power only. If necessary the time response can be improved but this may necessitate a machine designed specifically for the *QUAVER* system if ultra short recovery times are required. In particular, a larger than normal capacity exciter, working at a higher frequency in order to initiate corrective action more frequently, will be required to supply the higher forcing currents necessary. The performance will ultimately depend on the cost increase permissible, the main cost increase being due to the larger exciter. Of course, as anyone reading as far as this will know, constant voltage is not the only objective; constancy of frequency of the supply voltage is most vital, and

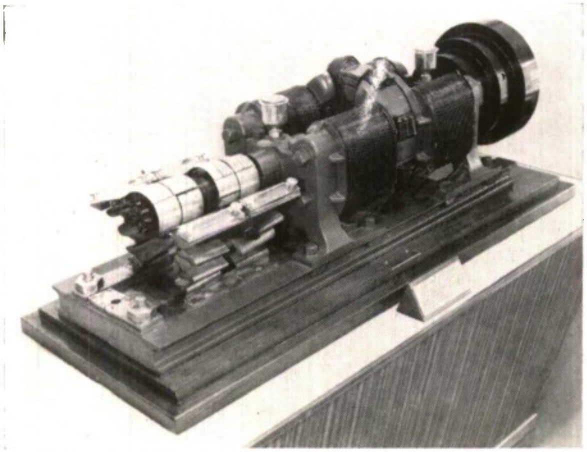


FIG. 12. Generator from H.M.S. "Inflexible," 1885.

parallel work is being carried out at A.E.L. on the governing of diesel engines driving large electrical generators, which is proving successful. These developments will make it easier to run machines in parallel in future, a desirable feature that is generally difficult to achieve at sea where the "infinite busbars" of the National Grid do not exist. The closer regulation possible with *QUAVER* may make it desirable in future to derive the sensing voltages from a point near the "centre of gravity" of the electrical loads or a point where the voltage regulation is most critical and thus avoid the loss of supply volts, through the impedance of the supply cables, affecting the regulation at the distant critical supply point.

Despite its very great improvement in performance this automatic voltage regulator is unlikely to be the last type to be used by the Navy. The first attempt at automatic voltage regulation used in the Navy can be seen in Fig. 12 where the correction is in the machine itself. Thus we have almost turned full circle. It may well be that *QUAVER* will also find a small niche in naval history at the appropriate time.

Acknowledgements

Acknowledgement is made to the Director of Naval Electrical Engineering, the Head of the Electrical Laboratory, and Captain D. A. Craddock, R.N. (Retd.) for permission to publish the material in this article. Mr. M. R. G. Wilkinson, Asst. Electrical Engineer, with Mr. A. W. Smith, carried out much of the earlier work on the system, which was continued and completed by the Authors.

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AN EXPERIMENTAL FAST-NEUTRON RADIOTHERAPY SYSTEM

M. F. Paris, R.N.S.S., D. W. Downton, R.N.S.S., and C. W. Glanford, R.N.S.S.
Services Electronics Research Laboratory

Introduction

A neutron generator system capable of producing 14 MeV neutrons at a rate of 10^{11} neutrons/second has been developed at S.E.R.L. for activation analysis. One of these systems has been loaned to the Christie Hospital and Holt Radium Institute, Manchester, where it is intended to be used for preliminary physical and biological experiments preparatory to clinical radiotherapy trials.

The interest has arisen because it is likely that fast neutrons will be more effective than conventional X-rays for radiotherapeutic treatment of oxygen deficient cells in tumours. This belief is supported by evidence from biological studies with 6 MeV neutrons from the Medical Research Council cyclotron at Hammersmith Hospital, London and with 14 MeV by various workers [1-7]. Current opinion [8-9] is that 14 MeV neutrons will prove to be the most effective radiation for neutron therapy and that the type of neutron generator developed at S.E.R.L. will be the most useful source.

Since 1963 the Christie Hospital and Holt Radium Institute at Manchester has been using an S.E.R.L. L-tube at 10^{10} neutrons/second [10-13] for preliminary physical studies. This has been replaced recently by the more powerful P-tube system at 10^{11} neutrons/second.

P-tube Neutron Generator

This tube produces 10^{11} neutrons/second of 14 MeV energy by the deuterium-tritium reaction in which a 1 : 1 mixture of the two gases at a pressure of 10 - 15 millitorr is ionized at one end of the sealed-off tube by r.f. power from an external coil and the resulting ions are accelerated by a potential of 120 kV d.c. to strike an erbium target containing an absorbed deuterium-tritium gas mixture. Mixtures of the gases are used so that the ratio of target gases is almost unaffected by exchange with the free gases, and target lives of 100 hours are obtained. A suitable electrode arrangement in the acceleration gap and target biasing minimize back-streaming electrons in the ion beam. Those that do get through are collected on the tube back-stop. A magnet coil provides a field to focus the ions near the extraction hole of the ion source. When not in use the free gas mixture is stored as a hydride in a replenisher of titanium powder which when heated drives off the gases to a pressure measured by a Pirani gauge integral with the tube. Fig. 1 shows the P-tube and Fig. 2 shows a diagram of the tube and the supplies necessary to run it.

FIG. 1. The P-tube.

P-Tube Container

The tube is mounted inside an oil-filled hermetically sealed cylindrical container which is 9 in. diameter and 42 in. high. It is suspended vertically from the lid of the container such that the neutron producing target is near the centre of the container and its r.f. and magnet coils are supported from a framework in the appropriate positions. As there is considerable heat dissipation from the P-tube, when operating, nylon pipes carry a supply of tetra-aryl silicate (TAS) coolant to various parts of the tube from a remote pump and heat exchanger assembly. The oil filling in the container while mainly providing against high voltage external breakdown also helps to cool the tube. A bag open to atmosphere compensates for oil volume changes with temperature. Electrical and coolant supplies for the tube all pass through sockets on the lid of the container so that it can be completely uncoupled and replaced in a matter of minutes. Fig. 3 shows the mounted P-tube ready for insertion in its container (not shown). The target end of the tube is screwed into the doughnut-shaped electrode with its associated coolant fittings shown at the bottom end of the central nylon support. In order below this come the shield electrode ring, probe electrode ring, the magnet coil, and the r.f. coil and finally the atmospheric bag in its cage attached to the bottom plate of the container.

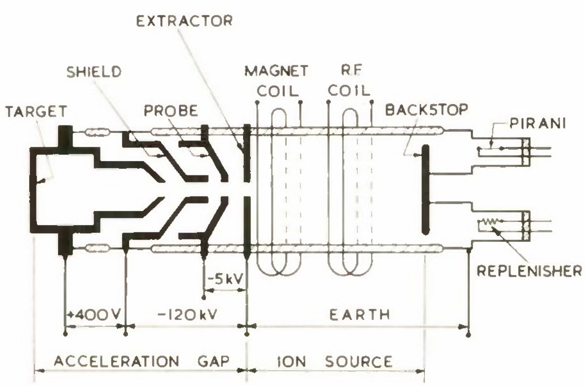

FIG. 2. Diagram of P-tube and its supplies.

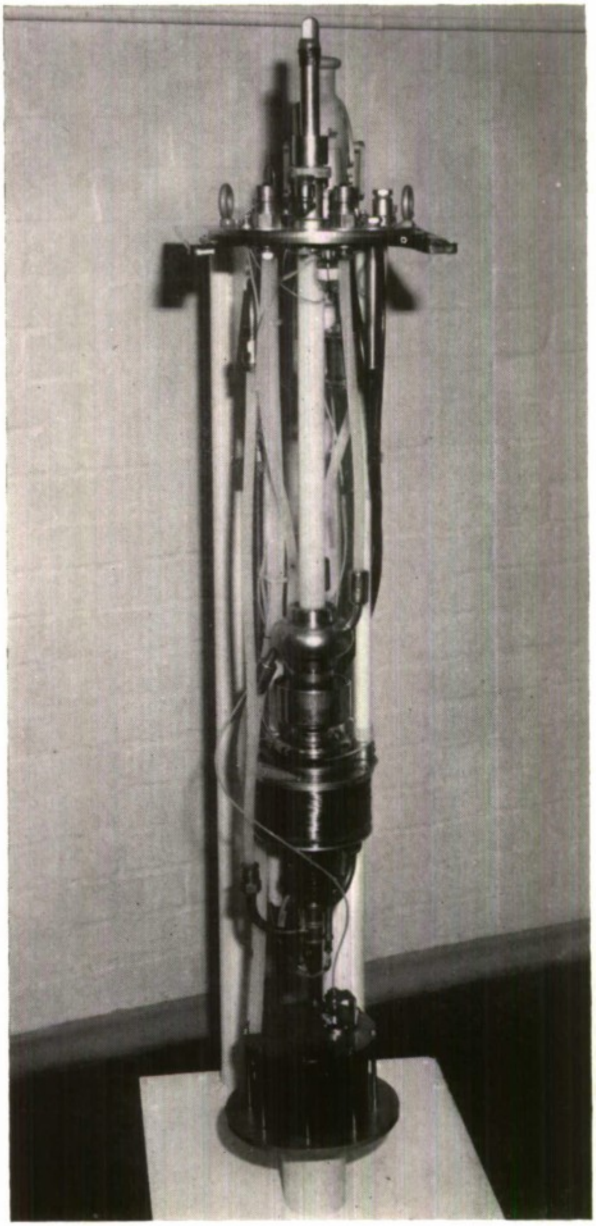

FIG. 3. The mounted P-tube.

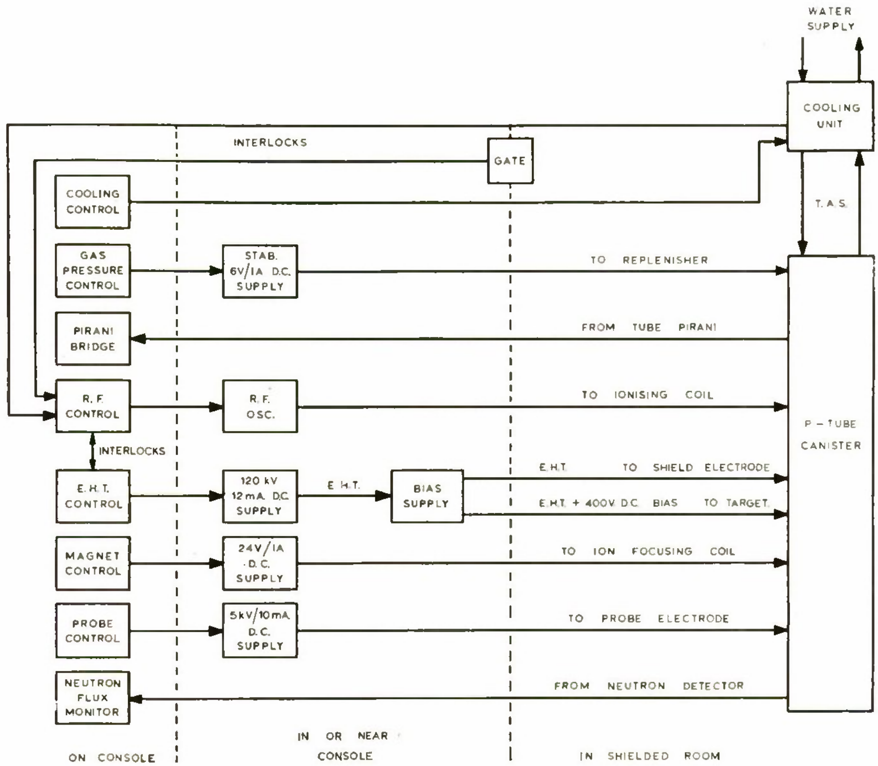

FIG. 4. Diagram of P-tube control system.

P-Tube Control System

The supplies required to run the tube are as follows:—

1. Replenisher heater supply.
2. Pirani bridge network supply.
3. R.F. oscillator of about 500 W output at 14 Mhz.
4. Focusing magnet supply.
5. Probe electrode voltage. (5 kV, D.C.)
6. Target shield supply (−120 kV, 12 mA D.C.)
7. Target bias (400V, D.C.).
8. TAS coolant (15 litres/minute).

Fig. 4 shows all these supplies in the form of a block schematic diagram. Control of the P-tube running conditions is effected from a console on which are displayed all relevant data such as voltages, currents, *etc.*, and indicator lights to show which circuits are closed. Variable transformers mounted on this console control the outputs of all supplies whether the power pack is in the console or outside it. A manually-variable motor-driven timer is also provided to control the neutron flux dosage time. The only control not on the console is for the radio frequency which is on a nearby rack within easy reach of an operator seated at the console. Fig. 5 shows the control position at Christie Hospital with the console at the right, shield bias supply in the centre, and r.f. oscillator on the left. The opening in the wall above the console is a periscope for viewing the inside of the shielded room where the P-tube is situated.

Christie Hospital Installation

The P-tube system is installed in a large shielded room with an external control room. Fig. 6 shows a plan of the various items of equipment as they are arranged within the facility. The P-tube con-

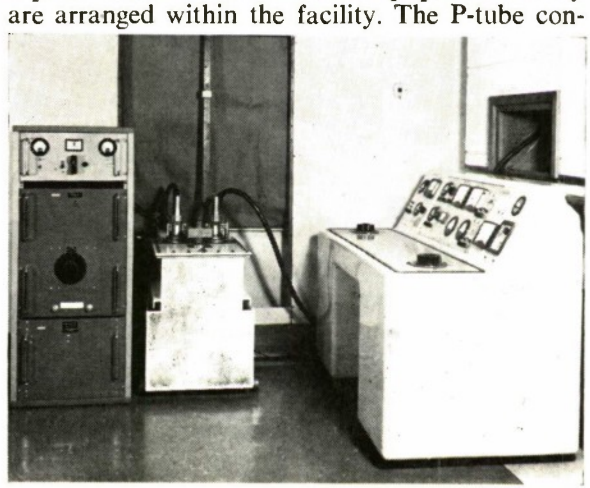

FIG. 5. Control position at Christie Hospital.

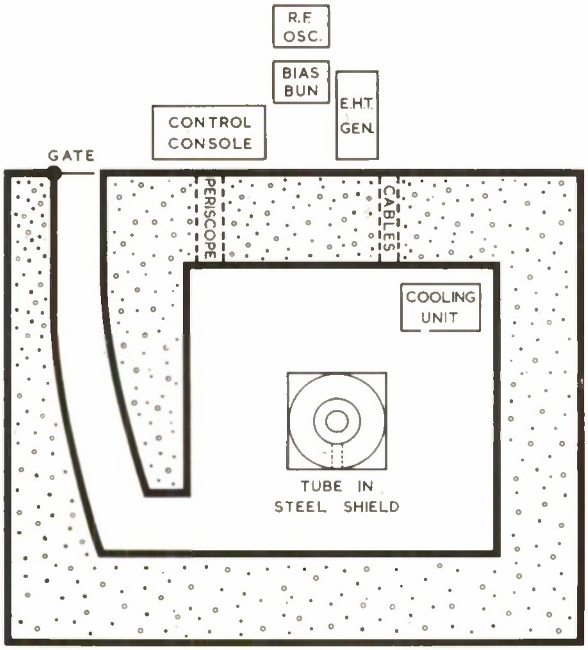

FIG. 6. Plan of Christie Hospital installation.

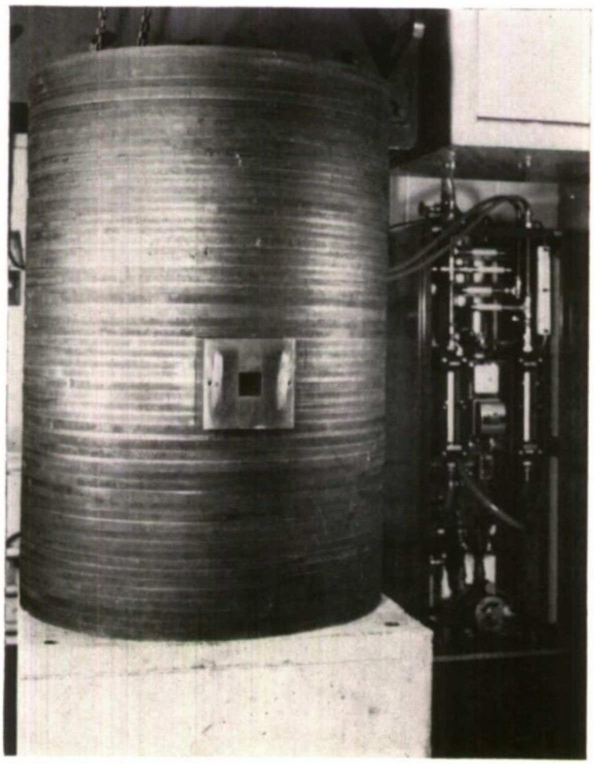

FIG. 7. The shield with collimator and cooling unit.

tainer is inserted into a shield made of one inch thick steel rings laid one on top of the other to form a cylinder with a 14 in. thick wall and a central hole of 10 in. diameter to cut off radiations in unwanted directions. A square aperture is left through the wall opposite the neutron producing target position for the placement of various collimators. This steel cylinder stands on a block of concrete in the middle of the shielded room and it is shown in Figs. 7 and 8. Fig. 7 shows a collimator fitted into the aperture and in Fig. 8 the shield is sectioned to show the position of the P-tube and collimator aperture. In the background of Fig. 7 can be seen the pump and heat exchanger

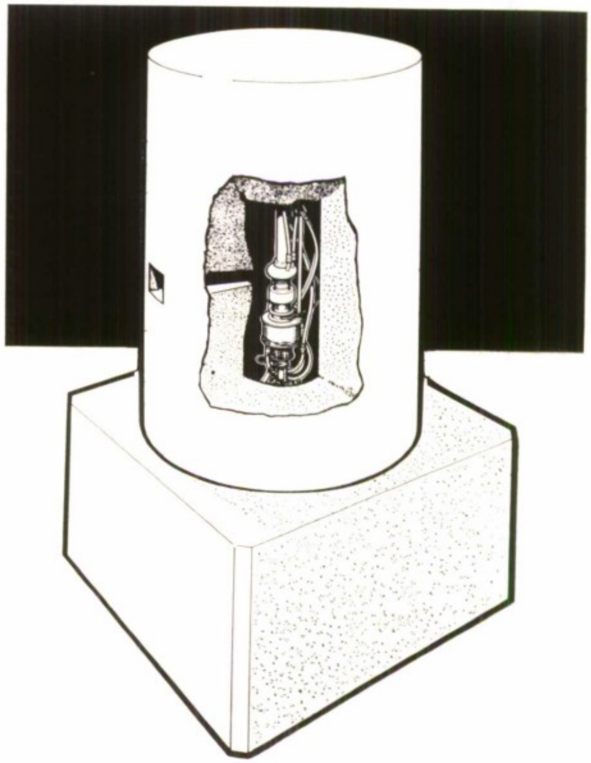

FIG. 8. Cut-away diagram of shield and collimator.

assembly. Fig. 9 shows a collimator about to be transferred from the storage rack to the steel shield.

The pump and heat exchanger assembly is placed inside the shielded room since the TAS coolant becomes appreciably radioactive during neutron production. The entrance to the shielded room has a gate which is interlocked to the tube running supplies so that no one can enter when neutrons are being produced. The console and other units are in the adjacent control room. Supplies from console to tube container pass through

skew holes in the shielding so that there is little neutron escape out of the shielded room.

Use of the System

The system has been used for collimation experiments and a certain number of biological experiments on tissue, barley seeds, and other organisms. These experiments have shown that it is possible to obtain fixed beams of 5 × 5 cm to 20 × 20 cm cross-section at 50 cm from the neutron source with a dose rate equivalent of 3 rads/minute of X-rays. Transmission through the steel shield is of the order of 4%. The quality of the beam has been analyzed both in air and in phantom and the provisional conclusion is that γ-ray contamination is not a serious problem but there may be a low energy neutron component.

Future Developments

For routine clinical trials this P-tube system at 10^{11} neutrons/second falls short of the required output by a factor of 10. Design studies at S.E.R.L. suggest that it is technically possible to produce a tube with an output of 10^{12} neutrons/second. Such a tube, to be known as the Q-tube, is now in the early stages of development and is being designed specifically for the radiotherapy application. It will be capable of mounting in a movable collimator shield so that the defined neutron beam can be correctly aligned with the patient.

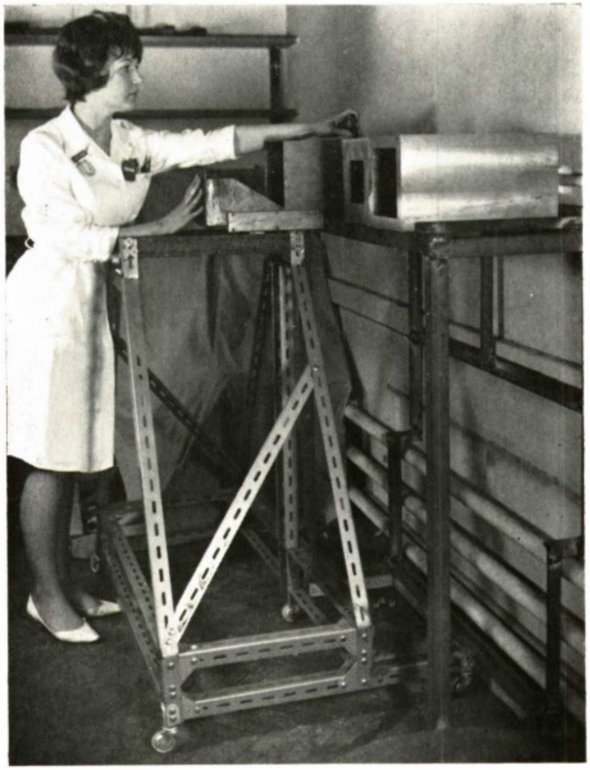

FIG. 9. Removing collimator from storage rack.

Acknowledgement

We are indebted to Dr. D. Greene of Christie Hospital for the use of his photographs and results.

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Anglo-American Co-operation in GAS LUBRICATION

Reported by A. G. Patterson, R.N.S.S.
Admiralty Compass Observatory

A third stage in technical liaison between British and American organizations engaged in work on or associated with gas lubrication was reached during April, when the first full-scale U.K./U.S.A. joint conference was held at The Admiralty Compass Observatory.

Previously, as a result of personal contacts in both countries, the American Office of Naval Research had invited A.C.O. to be represented at the quarterly meetings of its Gas Bearing Committee. Although it has been possible hitherto for A.C.O. to send representatives to only a few of the O.N.R. meetings, many of the American Group's members have paid individual visits to the Observatory and close links have been established.

The success of the O.N.R. Gas Bearing Group, which represents the major American gas bearing activities, and the prospects of a fruitful collaboration between U.S. and U.K. in this field, have encouraged A.C.O. to initiate a similar organization in Britain, which has already held two successful national meetings.

The Anglo-U.S. conference in April was attended by 11 American delegates representing the U.S. Government, universities and industrial organizations engaged in government-sponsored research. About 30 delegates of the British group represented parallel interests in the United Kingdom.

The proceedings took the form of a 1½-day symposium, but without some of the procedural formalities usually associated with the meetings of learned institutions.

After welcoming remarks by Mr. H. J. Elwertowski, Chief Scientist at A.C.O., Mr. S. W. Doroff of O.N.R., Washington, Administrator of the American Group, replied. During the meeting, British and American papers were presented in alternation, followed by brief discussion periods. Effectively, the subjects were reports by both sides of progress in various projects concerned with gas lubrication.

The opening speaker was Mr. D. A. Jones (Leeds University), deputising for Professor D. Dowson, who outlined the " new look " being taken at the subject of lubrication in Britain, particularly in education and research, as a result of the Jost Committee Report on Tribology to the government. (Note: the word " Tribology " is an all-embracing one meaning Lubrication and its allied sciences, officially recognized both by the government and the Institution of Mechanical Engineers.)

The first American contribution was shared between Dr. B. Sternlicht (Mechanical Technology Inc., Albany, N.Y.) and Dr. C. Pan of the same organization. Dr. Sternlicht gave a review of the interesting applications of gas bearings to heavy machinery now being made in the United States, including the utilization of process fluids as lubricants. Dr. Pan confined his talk at this stage to an assessment of the relative merits of gas bearing spherical, conical and spool-form gyro configurations and also announced a forthcoming M.T.I. publication on design data for gyro thrust bearings.

Mr. M. Lavender (British Aircraft Corporation, Stevenage, gave a review of B.A.C.s gas bearing work on gyros for A.C.O. and R.A.E. and included descriptions of some of the firm's air bearing commercial products, including a roundness measuring machine, workheads and wheelheads for grinders and a gyro test table.

Dr. L. Licht (Ampex, Redwood City, Calif.) described work he is doing on the stability of high speed rotors in foil bearings.

In the next British contribution, Mr. B. Dunne (Smiths Industries Ltd., Cheltenham), deputizing for Mr. R. W. Simons, gave an account of the very high precision of machining gas bearing gyro components made possible by the use of air bearing machine tools, enabling close tolerances of geometry to be achieved, even for flat surfaces, on a grinding machine without having recourse to lapping.

Professor H. G. Elrod (Columbia University, N.Y.) outlined the work of Columbia's Mechanical Engineering Department on foil bearings, associated generally with magnetic tapes for computers. He also outlined a mathematical technique used in analysis of ripple phenomena in foil bearings and their stability behaviour.

In a further contribution, Dr. C. Pan (M.T.I.) gave the meeting an assessment of gyro thrust bearing efficiency, particularly in falling short of theoretical performance by as much as 30% due to thermal distortions of thrust plates.

Professor V. Castelli (Columbia University, N.Y.) announced a review of numerical methods for solving Reynolds's equation, fundamental to most gas bearings, being undertaken at Columbia. He also described work on the effects of transient forces on rotor dynamics and referred to Professor Fuller's work in the preparation of a compliant surface bearing design manual. Finally he gave an account of some related work on the behaviour of elastomers used in these bearings.

Mr. J. Kerr (N.E.L., East Kilbride) summarized the work of N.E.L. in aerostatic and aerodynamic gas bearings and gave particulars of a recent development of a porous pad/compliant surface bearing.

In a joint presentation by Mr. O. Decker and Mr. J. McCabe (Franklin Institute, Philadelphia, Pa.), some of the work in gas bearings being undertaken by the Franklin was described, including tilting pad types, stability analyses, turbomachinery and cryogenic applications.

The work of R.A.E. Inertial Navigation Division on gas bearing gyroscopes was described by Mr. D. Faddy, who gave particulars of current work on a small semi-inertial-quality instrument of conical configuration and discussed problems of manufacturing it.

The final presentation was by Mr D. Young (Sperry Gyroscope, Bracknell), who gave an account of Sperry work in the development of the WS series of stabiliser gas bearing gyros for the Navy Department and also summarized the findings of a gas bearing gyro stability investigation, carried out by the firm under contract from A.C.O.

The afternoon of the second day was spent on a tour of inspection of A.C.O.'s own gas bearing laboratory and other R & D departments.

On the social side, a cocktail party was given at A.C.O. for all delegates on the evening of the first day, when valuable opportunities were presented of personal contact between British and American delegates with common interests.

A programme of visits for delegates was arranged for subsequent days of the week, comprising B.A.C.'s works at Stevenage, R.A.E. Farnborough and the Department of Engineering Science, University of Oxford.

The many expressions of appreciation received from overseas and British delegates, encourage those concerned at A.C.O. to hope that collaboration in this field may be perpetuated on both sides of the Atlantic.

The following six papers were presented at the Diving Seminar held at the Royal Naval College Greenwich on 12th March, 1968.

TECHNIQUES AND EQUIPMENT OF DEEP DIVING

Commander P. A. White, M.B.E., R.N.
Superintendent of Diving, Royal Navy

Before the physiologists—engineers—scientists and doctors are let loose among you, I think it would be wise to commence this seminar with our feet firmly on the ground (well perhaps just in the water). I intend, therefore, to look a little into history, to review the present state of the art in the Royal Navy, and take a brief look into the future.

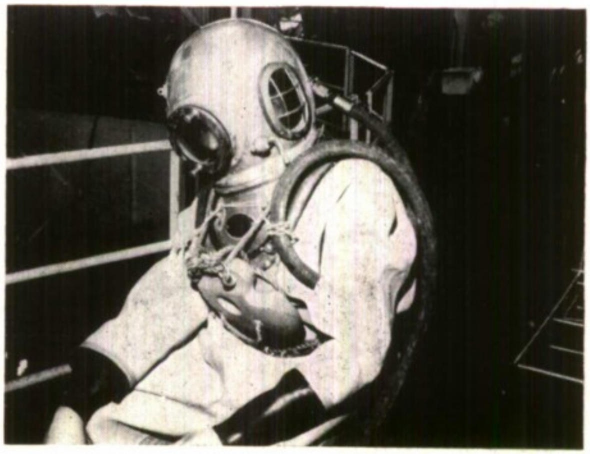
To those of you who are actually involved in commercial diving activities I apologise, and would ask them to bear with me if initially I cover basic ground. I consider this necessary, however, and I hope of value, because although many of you are involved in one or more aspects of underwater operations you may not necessarily see the diving problem as a whole.

If diving be defined, merely, as descending underwater and remaining there for a short period, then there have been divers in all ages. Man must have learned to dive almost as soon as he learnt to swim, but he must also have learned that his physiological structure, as an air breathing land creature, imposed very definite and narrow limits upon his activities underwater; limits which remained unaltered for many centuries and which have only been extended in recent times. Our first attempt to enter this foreign environment was confined to the limit of one deep breath, much the same as the Far East fishers to-day. This technique was probably followed by breathing through a reed or a piece of bamboo. It was not until the Middle Ages, loosely speaking, that we find attempts to supply air to a man underwater. Many odd devices and techniques were forthcoming until finally the copper helmet, standard, diving dress was evolved. The attendant problems of Nitrogen Narcosis, *Rapture of the Great Depths —(NARKS* to the R.N. diver), and Decompression Sickness accompanied the introduction of this type of diving. These problems will be dealt with in detail later.

Throughout to-day you will frequently hear the term *Deep Diving* and *Saturation Diving* mentioned. It might be appropriate at this stage to explain the meaning of these terms:—

DEEP DIVING—This is regarded as any dive deeper than 30 fathoms.

SATURATION DIVING—Is considered to be a dive of such a duration that even if the diver remained at depth longer he would have to pay no extra penalty in decompression time. In other words, *SATURATION*, as the word implies, means that the body has taken up as much inert gas as possible. This is the technique employed in SEALAB and by several U.S. commercial firms.



Standard (copper helmet) diving dress

History

Prior to 1933, diving in the R.N. was limited to depths of approximately 200 ft. Equipment used was the hard-hat standard dress, supported by hand-operated air pumps. In practice very little diving was carried out beyond 90 ft.

In 1933, the R.N. Deep Diving Committee recommended that the maximum depth limit be increased to 300 ft. At the same time mechanical air-pumps and the submersible chamber was introduced. It became evident then that the limit of air breathing had been reached. No real progress was then made until after 1946.

Oxy-helium trials were carried out between 1946 and 1948, as a result the R.N. diving capability was increased to 360 ft for a maximum time on the bottom of 20 minutes only. Further research was carried out and in 1954, still using hard-hat equipment, the maximum depth for work was extended to 410 ft for short periods. In 1956 one dive was achieved to 600 ft to prove that limited work could be carried out at this depth. In fact this dive was for a very short period and almost amounted to a bounce dive.

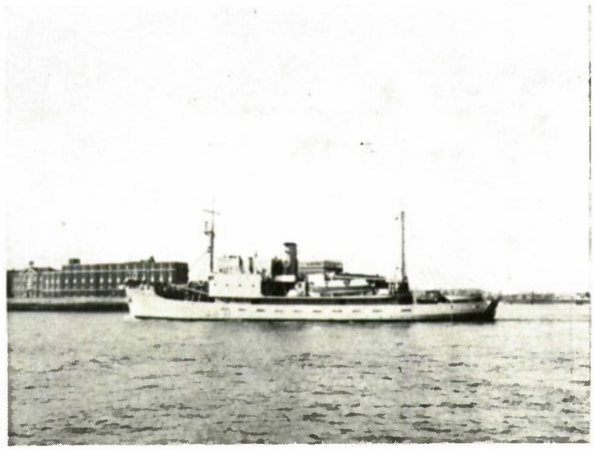
Because of a change in submarine escape policy to which the Deep Diving programme was allied and the introduction of the Free Ascent method for escape from a sunken submarine, operational diving was no longer required to these depths and in this role. Diving in the R.N. was then limited to 180 ft.

Of the two R.N. Deep Diving ships—*Kingfisher* and *Reclaim*—*Kingfisher* was sold to the Argentine and *Reclaim* was saved from a similar, or worse fate, by the foresight of a staff officer in the Admiralty at the time. *Reclaim* was retained as a Minecountermeasures Support Ship (still keeping her deep diving equipment for possible future use). Without *Reclaim* to-day we would not be in the deep diving business. Captain Blake, the officer who foresaw this return to Deep Diving is now in the Directorate of Weapons (Underwater).

In 1962, deep diving trials recommenced with a five-year programme aimed at producing a Continental Shelf capability of 800 ft. To achieve this it was decided that a depth of 1200 ft should be our goal.

A series of laboratory experiments, and sea trials, terminated in June 1965 when a total of 18 divers operated at 600 ft for periods of up to one hour. By this time the hard-hat standard equipment had been replaced by lighter equipment designed by the Admiralty Experimental Diving Unit at Portsmouth.

Unfortunately this 600 ft capability represented the limit in depth set by the old equipment fitted in H.M.S. *Reclaim* and the decompression schedules could still only be regarded as experimental. No progress has since been attempted towards the ultimate aim of this plan. There ended the first lesson.



H.M.S. " Reclaim "

R.N. Diving Structure and Equipment

I think at this point I will cover the diving structure in the R.N. and the equipment used by the various grades of divers and their capability. There are four grades of diver:—

Ship Diver
Part-time—anyone (officer/man, padre/cook. Four weeks training on compressed air. Duty—diving to 120 ft—bottom search (infernal machine placed by unfriendly natives).

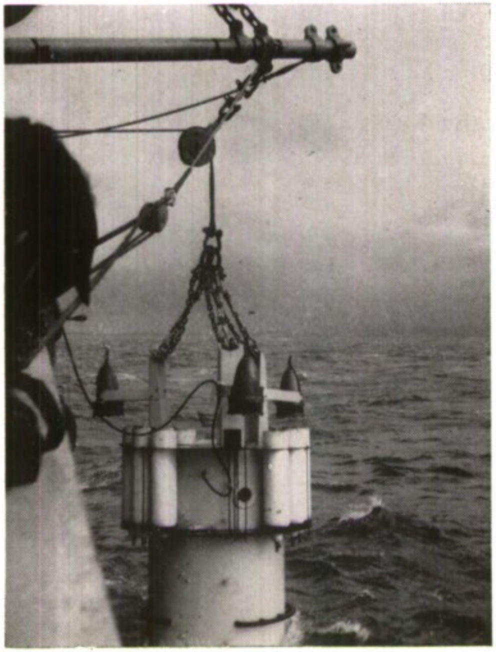
Artificer Diver
A ship diver—extends his trade underwater—emergency repairs.

S.A.R. (Search and Rescue) Diver
Intrepid aviators—plane guard.

Clearance Diver
Full-time—professional—250 ft on air.
Equipment—special.
Deep Diving—volunteer.
For Explosive Ordnance Disposal.
Six months training—highly skilled.

Deep Diving—Present System and Techniques

In the Royal Navy, deep diving at present is based on a technique of employing a submersible compression chamber with transfer-under-pressure facilities at the surface. Divers are lowered to the working depth in the submersible compression chamber. During descent, the lower door of the chamber remains open, the ingress of water being prevented by filling the chamber with oxy/helium



The submersible compression chamber slung from H.M.S. " Reclaim "

A diver at depth alongside the S.C.C.

gas at the appropriate pressure. After completion of work outside the divers re-enter and the lower door is closed, and the chamber is winched to the surface where it is mated to the larger deck-mounted transfer-under-pressure chamber. Pressure between the two chambers is then equalized and the divers transferred to complete their decompression in relative comfort.

Ideally, the submersible compression chamber must be able to withstand an internal pressure equivalent to the maximum depth of dive in order that, in an emergency; the diver can be immediately brought to the surface, transferred to the larger compression chamber where he can receive medical attention should this be necessary.

During R.N. trials, it was essential to be sure of the precise gas mixture being breathed, and divers therefore used open-circuit breathing apparatus whereby the gas was exhaled directly into the sea. There is no doubt that a requirement exists for a semi-closed or completely closed circuit breathing equipment to conserve helium.

Techniques for operating divers from surface ships or installations must depend to a certain extent on the task. In general, the R.N. must anticipate the need to operate in open sea. This introduces a considerable seamanship problem, location, accurate mooring, precise plumbing of the submersible compression chamber over the task and finally, operating in tidal and/or bad surface conditions. Many of these problems are minimised or are not applicable when operating from an oil-rig.

In order to cover the problems of techniques and requirements for Deep Diving it would be wise to take " an all round look in high power "—as they say in the Submarine Service—at the project as a whole. Experience has shown that only by complete team work throughout between the sailor, the scientist and the doctors can success be achieved. The most important aspect is co-ordination. This applies equally to a record dive or a comparatively simple task in shallow water. I propose to cover briefly the chapter of events that go into the production of any new operational technique, or piece of Deep Diving equipment, after the naval staff division have laid down the requirement and the aim.

I, as the Superintendent of Diving—the user—co-ordinate the many aspects and diverse talents that go into producing the new operational techniques—and, I am finally charged with the responsibility of accepting it into service.

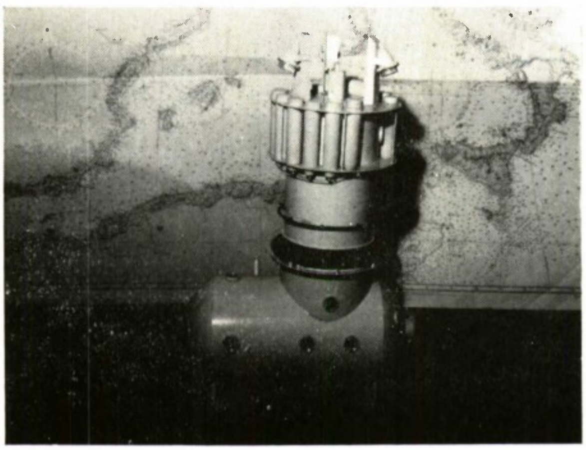
It is the naval diver who is the human subject and the naval doctors who supply the medical coverage throughout.

The engineers within the Royal Naval Scientific Service together with the naval diving officers—again the user—who provide the design of breathing equipment, ashore and afloat chambers, submersible compression chambers and transfer-under-pressure complexes, including the means of controlling the environment. In this, I include chamber panels, temperature control, CO_2 scrubbers, de-humidifiers, *etc.* They are also responsible for communication and closed-circuit television coverage.

The production of Decompression Schedules for trial by humans are calculated and issued by scientists of the Royal Naval Scientific Service, from the Royal Naval Physiological Laboratory at Alverstoke.

To summarize, it is the Admiralty Experimental Diving Unit that produces the equipment—the Royal Naval Physiological Laboratory that gives us the Decompression Schedules, the R.N. medical officers who provide the coverage for any therapy that may be required (we always Bend one or two) and the R.N. divers that produce the operational " know-how " and have the responsibility for trials and acceptance into service . . . and it is I who sits at the end of that long Court Martial table should things go wrong !

H.M.S. *Reclaim*, to-day has an emergency capability to diving to approximately 400 ft using oxy/helium breathing mixtures. You may recall that a ditched Buccaneer aircraft was recovered from a depth of 370 ft 10 miles south of the Lizard in 1966. The schedules used then are still not completely Bend free and should not be used without adequate precautions which will be covered later.



A model of the proposed new S.C.C. and shipborne chamber for H.M.S. " Reclaim ".

Deep Trials Unit

Situated within the confines of the Royal Naval Physiological Laboratory at Alverstoke, the Royal Navy has a Deep Trials Unit which consists of a complex of chambers with a " wet " section. This installation is capable of simulating " wet " dives to a depth of 1200 ft. It is also possible to simulate all types of climatic conditions within the chambers. All new diving schedules are first tried in this complex before being taken to sea. Unfortunately, there are indications that although the pressure conditions and the temperature conditions can be exactly simulated within the Deep Trials Unit, some difficulties arise when the diver actually goes into the sea.

Personnel

Various problems have shown themselves in the practical application of deep diving techniques, not the least of which is the now accepted fact that one cannot produce a safe diving schedule to cater for everybody, including one's granny ! There is no doubt, in my mind, that some men make better and safer divers than others. It is also a fact that an " in practice " deep diver is less likely to get into trouble than one who is out of practice. Within this trouble I also include " bends ". I also personally believe that the deeper one goes the higher percentage of incidents one will have to accept.

Keeping the diver warm presents quite a problem. In addition to the obvious difficulties of diving in cold water, breathing helium exaggerates the body heat loss. Obviously, there is a very real requirement for heated suits. At present, the R.N. is making do just adequately with nylon fur underwear. These have been proved to be far superior to the normal standard woollies.

Communications

Good communications present quite a problem with all deep diving and in particular, when the diver is breathing a helium mixture. Various organisations throughout the world are experimenting with the problem of converting the noise that comes back from the diver to something intelligible. It may be possible in the future, to unscramble this noise.

General Points

Experience has shown that if a diver contracts a bend it is sometimes necessary to recompress to the maximum depth of the dive to obtain relief. Because of this, the R.N. considers that it is essential to have a transfer-under-pressure system capable of transferring from the maximum depth of the dive.

Whilst carrying out experimental diving on a new schedule, it has been found necessary to have a helium atmosphere capability in the chamber inboard,

The provision of a simple, closed-circuit television to observe the diver during his dive has proved invaluable, especially in saving the grey hairs of the supervisor !

The problem of diving in a tideway still has to be solved.

I also appreciate that a submarine-type vessel with a diver lock-out capability is undoubtedly the best diving platform for deep diving activities.

Future

I think that it is now common knowledge that the Royal Navy intend to return to Deep Diving trials. H.M.S. *Reclaim* has been saved—yet again—from a fate worse than death—she will be with us for another seven years. In broad terms this means concentrating, initially, in the 600 ft area and will include saturation diving. There would appear to be no major reason why this should not be achieved by 1971 or 1972.

Now—a final observation—there is no doubt that without the keen co-operation of the engineer, physiologist, medical officers, scientists and sailors the production of any new diving technique or equipment would not be possible. With such teamwork, we know, that (given the right facilities) diving to almost any depth can eventually be achieved. It must be remembered that diving is neither a straightforward engineering, physiological, or medical science. It is basically a seamanship problem, supported by all these sections of science. And we would be foolish indeed to ever forget *the greatest single factor* in our effort to plumb greater depths for longer periods, is the diver himself—the man in the sea, on the end of an air pipe feeling cold and very alone. Without his skill, determination, faith and courage—we would all be wasting our time.

Diving Seminar 1968

SOME PHYSIOLOGICAL FACTORS IN DIVING

H. V. Hempleman, R.N.S.S.
Royal Naval Physiological Laboratory

For men to work freely in the sea it is necessary to breathe gas at pressure. Oxygen being the only gas that supports life it would be reasonable to enquire why any other gas is used. The answer is that high pressures of oxygen are harmful and there are well accepted values for the time which it is safe to breathe pure oxygen at any given pressure level. At 33 ft under the sea *i.e.* at two atmospheres total pressure it is inadvisable to breathe oxygen for more than 30 minutes. Oxygen is therefore a relatively poor gas for diving purposes except for very shallow work. Obviously one then turns to air to discover how much better off one is with this as a breathing medium. Here we must note that 1/5 of the air pressure is oxygen and 4/5 nitrogen. If therefore a man goes to a pressure of air of 10 atms. total, then 1/5 of this pressure is oxygen, that is 2 atmospheres, and as has just been stated it is not possible to work safely at such a pressure of oxygen for longer than 30 minutes. Now 10 atmospheres pressure of air is equivalent to 300 ft pressure of sea water, thus the limit of diving safety, as determined by the oxygen pressure is 30 minutes at 300 ft. If a diver is taken to 66 ft under the sea, where the total pressure on him is 3 atmospheres, then as 1/5 of this total pressure is oxygen he is breathing an oxygen pressure of 3/5 of an atmosphere, and such a pressure of oxygen is the maximum permissible for prolonged breathing. In Fig. 1 the limits of use for pure oxygen are shown in the solid black zone, which is quite small. Air covers a vastly greater range of pressure-time possibilities, but

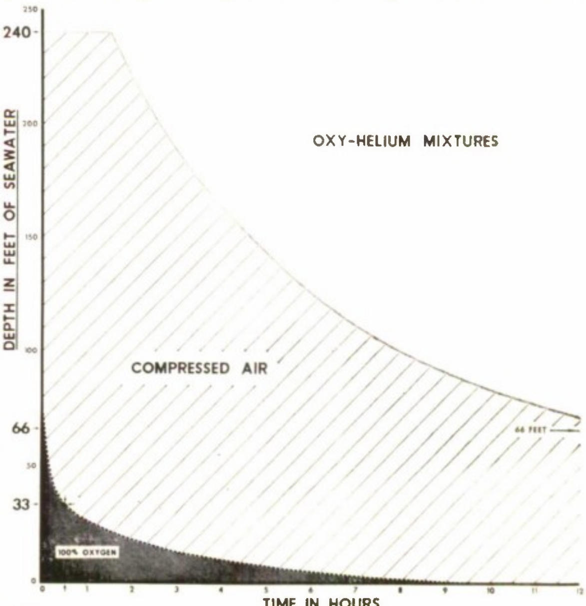


FIG. 1.

it may be seen that 66 ft or 30 p.s.i.g. is the greatest pressure for prolonged compressed air breathing, and for reasons I will shortly explain, 240 ft is the greatest pressure possible and then only for a relatively short period due to its oxygen pressure. Any attempt to stay at pressure for longer periods will necessitate a shift to lower oxygen levels, and preferably a change from nitrogen in air to helium.

Recently at the R.N.P.L. we have issued a set of air decompression tables for depths from 100 ft to 240 ft. These tables incorporate for the first time anywhere the limits of performance on compressed air as determined by the oxygen pressure of the air. Also incorporated in these tables are several other ideas that have accumulated over the past few years. However it must be understood that the tables have not yet been fully tested. There will always be some decompression sickness on any fixed set of routines like these. The hope is that on the new tables the number of decompression sickness cases will be much less than would have been expected from using the old procedures. It will have been observed that these air tables only take men to 240 ft depth. Now why? To answer this question one must examine the effects of nitrogen pressure in the air. Nitrogen does not react chemically with the body, but it certainly does nevertheless interfere with the functioning of the brain in some way and can produce a state of stupefaction and unreliability at pressure which has been called nitrogen narcosis. This narcosis is just detectable on most normal men at 100 ft depth and is grossly obvious at 300 ft. Somewhere around 240 ft it is generally agreed that the N_2 content of air is too great for regular reliable work, except by very practised divers. Therefore to dive deeper than 240 ft means that some gas other than nitrogen has to be coupled with the appropriate oxygen pressure. There are only three possibilities, neon, hydrogen and helium, or of course various mixtures of these three. Neon has been tested at R.N.P.L. and the theoretical expectations that it would be better than nitrogen were justified. However it is not very greatly better, and is prohibitively expensive both of which facts have led to it being rejected for further work. Hydrogen was first breathed at pressure in 1941 in this country, and later used by the Swedish Navy in certain experimental sea dives, at depths somewhat in excess of 400 ft. From all this work it is quite clear that hydrogen represents a real possibility for deep diving. Unfortunately it is of course explosive with most concentrations of oxygen and is therefore an extremely difficult gas to work with from a safety point of view, and we have not pursued any experiments on hydrogen. Consequently all our deep diving experimentation has been done using oxygen-helium mixtures only. No mixtures of helium with other inert gases have been used, as these would further complicate an already complex situation and make experimental interpretations even more difficult than at present. After some preliminary experiences of the difficulty of mixing and analyzing oxygen-helium gases on board a diving vessel it was decided to use mainly three mixtures, of fixed composition; these were 5% O_2, 95% He, 10% O_2, 90% He, 20% O_2 80 He. Once again it must be borne in mind that the oxygen pressures of these mixtures will define their limits of usefulness, just as for air considered previously. Suppose the diver is at a pressure of 40 atmospheres breathing the 5% oxygen mixture, then 5% (*i.e.* 1/20) of the 40 atmospheres is oxygen pressure which is of course 2 atmospheres. As we saw previously 2 atmospheres of oxygen can only safely be breathed for 30 minutes. Thus

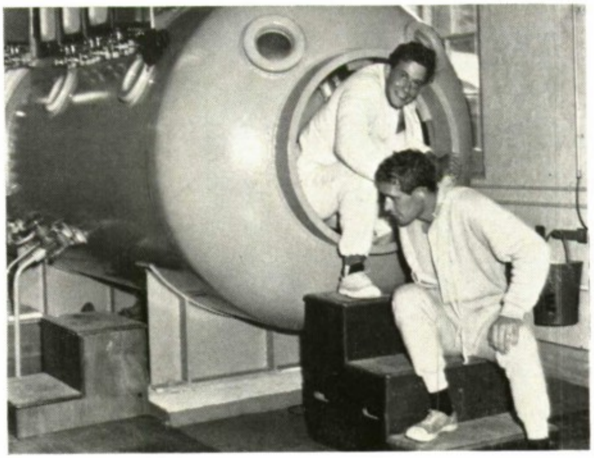


FIG. 2. Volunteers leaving the three-compartment " dry " chamber at R.N.P.L.

30 minutes at 40 atmospheres pressure defines the upper level of this gas composition. Now fortunately 40 atmospheres represents a pressure of sea water in excess of 1200 ft so that the very great range of possible dives offered by these mixtures can be seen. Some further physical factors must be settled before proceeding to actual dives. It was decided that a speed of descent by the Submersible chamber greater than 100 ft per minute was not desirable, consequently all descents to depth by our divers occurred both in the experimental chamber dives, and in the subsequent sea testing, at 100 ft per minute. This rate of descent to depth has been found to cause some difficulties with dives at depths in excess of 500 ft due to the onset of trembling of the hands, which makes fine work difficult. At 800 ft some men are quite grossly affected with these helium tremors, although they are quite capable of moving about and performing the normal divers' tasks properly.

In Fig. 2 volunteers are seen leaving a chamber. They wear brushed nylon suits for warmth because helium is a very good conductor of heat and makes the subjects feel very cold, on even quite warm days. They wear no breathing apparatus at all and move about freely inside the chamber rather as they would in a caisson or undersea house. This particular chamber is a three-compartment one capable of being compressed to a pressure equivalent to 800 ft under the sea. The decompression from such deep dives takes many hours, and if accompanied by decompression sickness can take days. We have consequently learned a good deal of the physics and physiology of life at pressure.

One of the first important physiological factors is to discover how quickly helium gas saturates the relevant body tissues. This was first carried out on large animals when we discovered that contrary to some ideas the helium saturated very much more rapidly than nitrogen. Repeat experiments on human volunteers seemed to show the same general picture. Helium saturates body tissues more rapidly than nitrogen but equally helium is removed from body tissues more rapidly than nitrogen, and therefore the pressure-time course of a helium decompression will be quite different from that of an air decompression. How should one carry out this decompression to achieve the most rapid consistent with safety return to atmospheric pressure ? One can either reduce the pressure continuously along some pre-conceived path, in which case the various possibilities are enormous. Should one let off the pressure rapidly at the start, and then more slowly later, or the other way around, or perhaps a steady rate of drop of pressure at so-many feet per minute as employed by the U.S.N. in their *Sealab* experiments. This bewildering array of possibilities to be tested by human volunteers, in the only way known at present, which is to see whether painful bends occur, or perhaps even more dangerous possibilities than just bends pains at these very great pressures was one reason why we took an experimental short-cut and adopted discontinuous decompression procedures. In other words we made a certain stay at a fixed steady pressure and at the end of this time we rapidly lowered the pressure on the man to some new value and waited to see whether this was a safe move, *i.e.* stage decompression. By means of these large pressure drops and periods of waiting following each drop, it is possible to plot a path back to the surface. After completing some successful exposures of 4 hours at 300 ft, 15 minutes at 300 ft and 16 minutes at 500 ft a theoretical examination of the data was undertaken. It became clear that a simple graphical plot of the square root of the time versus the pressure gave a straight line, within the experimental limits of the observations. This observation was then used to predict 1 hour dives at 450 ft. and 600 ft. and 20 minute dives to 800 ft. In the dry chamber with hard work on the bottom and even with sometimes not the fittest of men as volunteers all these dives were carried through with only very minor complaints, none of which were worth recompressing. A total of 18 men passed through these procedures and this whole series of dives must be considered very encouraging. The big snag always arises when we try to transfer our dry chamber results into the sea. In the experiments the men are kept warm in dry chambers, wear no mouthpieces or breathing gear of any sort—they just breathe freely from the chamber atmosphere, are in close touch with the outside world, not subject to ship motion, not subject to changes in blood flow caused by immersion in perhaps quite cold water, no suits to cause nips or local constrictions of blood flow. To repeat the dry chamber conditions at sea is not impossible but difficult. It is possible to employ heated undersuits, conventional helmet divers and suchlike aids to better underwater performance at these deep depths.

Finally a statement on certain variations on the main theme. We have tried using air as a decompression medium for deep dives and although there are undoubtedly marked advantages to be gained in certain types of diving it is, in general, not a good idea. We have tried it ourselves, and two other independent diving groups who have used the chambers at R.N.P.L. to exploit their own ideas have also tried air on the stops, and in the end abandoned it in favour of staying on oxy-helium all the way to the surface. Oxygen also does not confer the benefit expected and we do not do very much oxygen breathing on the stops. Once again it is fortunately possible to state that we have watched other independent groups at R.N.P.L. reaching the same rather awkward conclusion. For ourselves we have realised that the cost of deep diving is such that attempts to save money on a few cubic feet of helium, which is why most people suggest air or oxygen, is not worth bothering about. Another suggestion made was that by making large sudden pressure changes we were creating bubbles in the body and that this was obviously a bad thing to do and would cause a great lengthening of the decompression requirements in order to keep the bubbles from growing. Accordingly a few comparison dives were made between our stage methods and other totally different decompression systems.

Fig. 3 shows the time-pressure courses of decompressions following a dive of 4 hours duration at 300 ft. The stage decompression system is used for them all, but in one case a small number of

big pressure changes is performed and in the other two cases much smaller pressure changes are performed, both at the start of decompression and throughout. Despite these attemps to alter the outcome of the dive it can be seen from the black circles that bends occurred from all three. The big drop method we were employing was certainly no worse than these other modifications, and in fact looked more promising. The eventual safe decompression time for normal men for this dive came out at 20 hours. It became quite clear as a result of these tests that there would be no marked advantages in changing the stage decompression approach, and if anything there would be disadvantages. To give some idea of the variations in safe decompression times that are being attempted it would be better to compare two groups outside the U.K. operating undersea house techniques. A French doctor and German scientist recently decompressed themselves without incident after a stay of 100 hours, just over four days, at nearly 800 ft, in 78 hours. Decompression from this dive using the current *Sealab* techniques would require 200 hours. This is a difference of five days in decompression time, which to say the least, is worth further examination. As we have not done such prolonged dives one can only state that our prediction would in typically British fashion be somewhere in-between but leaning much more closely to the shorter European times.

A word now on what is an acceptable decompression procedure. Let us assume that all fatal and very serious forms of decompression sickness have been reduced to rarities, then there will still be a risk of less threatening but painful conditions needing therapeutic recompression. Let us further assume that adequate recompression facilities, about which you will hear shortly, also exist. Then, everyone's ideas of a suitably low level of decompression sickness vary considerably. The tunnel workers consider a 2% incidence of bends to be the maximum permissible and this order of trouble influences our thinking, but there are

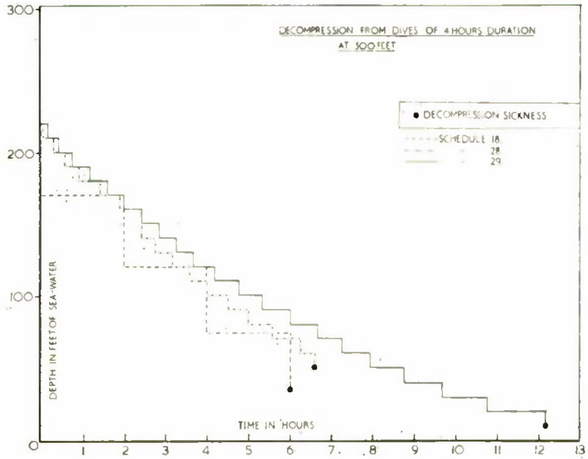


FIG. 3.

people to whom we have talked who consider that the 20% bends incidence which we have from time to time obtained in the deep dives at sea very acceptable. After all, four out of five got away without halting the diving and giving a recompression, not bad for five and 600 ft diving.

Lastly it might be asked, there is a nitrogen narcosis effect and a neon narcosis effect, is there a helium narcosis effect and at what pressure therefore will helium cease to be useful? One can only say that human measurements at 800 ft depth showed no signs of a helium narcosis effect, that large animals have been placed at a depth equivalent to 1,900 ft and did not appear to suffer any ill effects from this, and we ourselves have recently been testing small mammals at depths equivalent to 3,000 to 4,500 ft under the sea and again the animals appear to survive and live normally after their experiences. The future possibilities for helium diving therefore must be viewed with cautious optimism. The main thorn in the side of further progress is undoubtedly the problem of safe decompression.

SAFETY AND MEDICAL ASPECTS OF DEEP DIVING

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Royal Navy Physiological Laboratory

There are many aspects to deep diving safety, but for the purposes of this brief review we are concerned with only the human aspects. I am not going to cover those associated with the problems of seamanship and of engineering. Before we outline the basic principles of safety, I think it would be wise just to summarize very briefly the hazards of diving.

THE HAZARDS

The Direct Effects of Pressure

The body behaves as a fluid, with the exception of those spaces which contain air. Therefore only the air-containing spaces are affected by pressure and provided that the body is supplied with gas compressed to the pressure of the depth of the diver, then no untoward effect will occur.

Compression Barotrauma. If for some reason an air space is isolated then during compression the gases within will obey Boyle's law and cause distortion of the surrounding tissues. This affects the sinuses, the teeth, the ears and, under particular conditions of standard diving, the entire chest, a " squeeze ".

Decompression Barotrauma. On decompression there is an expansion of the gases in all the air-containing spaces and, again, provided the openings to these spaces are patent the expanded gas is able to vent from the body quite safely. If the gas is trapped in the lungs the effects can be fatal. It may rupture the lungs and may lead to intravascular bubbles of gas lodging in the brain and causing death.

Increased Gas Density. A third direct effect of pressure is the increased density of the gas. At 10 atmospheres absolute, 300 ft of sea water, the density of the gas is increased ten-fold and this puts an extra load upon the lungs. Bodily effort is limited by the breathing capacity of the individual and the secondary effects within the body lead to disorientation and possibly an accident.

Indirect Effects of Pressure

The second main category of hazards are the indirect effects of pressure, the effects of the so-called inert gases, nitrogen, helium and even hydrogen. Acute oxygen poisoning leads to epileptic fits and long-term oxygen poisoning leads to damage of the lungs. You have also been told about the uptake of inert gas by the body and thus the importance of adhering to calculated decompression schedules. Decompression sickness will still occur in spite of such schedules, though to a lesser incidence than without them, following nearly all deep diving.

The final indirect effect of pressure is that prolonged exposure to pressure will cause an alteration in certain constituents of the blood.

Effects of Breathing Apparatus

The third group of hazards are those due to particular forms of breathing apparatus; here I am considering only the semi-closed re-breathing apparatus which is commonly used to conserve oxy-helium gas. We have used open-circuit apparatus because each exhaled breath is passed straight into the sea and each inhaled breath is therefore of pure, fresh oxy-helium. In the semi-closed apparatus however the carbon dioxide is removed by soda lime and a further flow of gas replenishes the oxygen used. In these forms of apparatus there are therefore additional hazards, carbon dioxide poisoning and, secondly, hypoxia which causes a loss of consciousness with no warning.

The Physical Effects

The physical hazards include *verbal communications.* There is not only a distortion effect due to pressure itself but also an effect which is specific to helium. Good verbal communication from the diver to the surface is essential. *Fire risks,* due to the high partial pressures of oxygen, need to be considered. *Neutral buoyancy* is not exactly a hazard and is most important because it affects the ergonomics of work underwater, but it is important as a contributory factor because if vertigo occurs underwater, particularly with the usual poor visibility, the seeming weightlessness gives the diver no bodily sensations of position and has, on occasion, led to disorientation and thus accidents. The final effect of the sea is that of *extreme cold* against which of course the diver must be protected. For dives of worthwhile duration it is necessary to discuss the designs of heated suits.

SAFETY

Before the Dive

Pre-selection Tests. Is there any value in pre-selection tests? Particularly for oxygen poisoning or bends? The answer, regretfully, is no. Most deep divers are chosen by the process of natural selection. From the divers with whom one has to deal the unsuitable candidates have already gone.

Annual Medical Examination. The diver must be fit enough to undertake hard physical exercise and he must also be fit to go under pressure. His teeth, sinuses, ears and chest X-ray must all be normal. There is also the need for psychological fitness, the ability to remain clear-headed under extremes of stress, but in my opinion there is no requirement for the medical practitioner to assess this. It is part of the natural selection which is already complete.

Special Investigations. There are certain investigations required of every deep diver in order to have them available as a base line for some future occasion. The electroencephalogram, the audiogram and X-rays of the joints and long bones are needed.

Immediate Pre-Dive Check. One must ensure that the diver has no upper respiratory tract infection and is not suffering from the dehydrative effects of excessive alcohol. He should be in a good state of physical training and also, perhaps, in the state of diving "work-up".

During the Dive

Stand-by Diver. The first safety consideration is best illustrated by an actual incident. Using open-circuit apparatus, so there was no question of any CO_2 build-up due to the use of inadequate or inefficient soda lime, two divers were working extremely hard at about 360 ft on oxy-helium. Both suffered the same unusual effect, both became quite unable to help themselves particularly when they were to a certain degree fouled with their hoses. It took some minutes of rest before the divers were capable of assisting each other.

This demonstrated that when two men are sent down in a submersible chamber, one should go out to do whatever work is required and the second should remain within the submersible chamber ready to assist the first should he require it.

Communications. The second consideration, which on that occasion we had previously insisted upon, is that of efficient communications. When deep diving is done there shall be at least a closed circuit television camera with a wide angled lens in the submersible chamber so that if surface control wishes to ask a question the divers can be seen to make a visual response. There is no doubt that the presence of this facility minimized the seriousness of this particular incident. Eventually electronic unscramblers will be available to reconstitute oxy-helium speech but until then we must rely on codes such as hammer taps and on visual communications.

Atmosphere Control. When the diver is no longer in the water he discards his breathing apparatus and decompresses with his attendant, breathing chamber atmosphere. The engineers will describe in more detail with the principles of controlling an atmosphere within fine limits. At this stage it is merely necessary to point out that the oxygen should be between at least 0·2 of one atmosphere pressure and 2 atmospheres pressure for short exposures, but since most deep diving is prolonged the upper limit of oxygen should be 0·4 atmospheres. Although a maximum partial pressure of carbon dioxide of 0·03 atmospheres

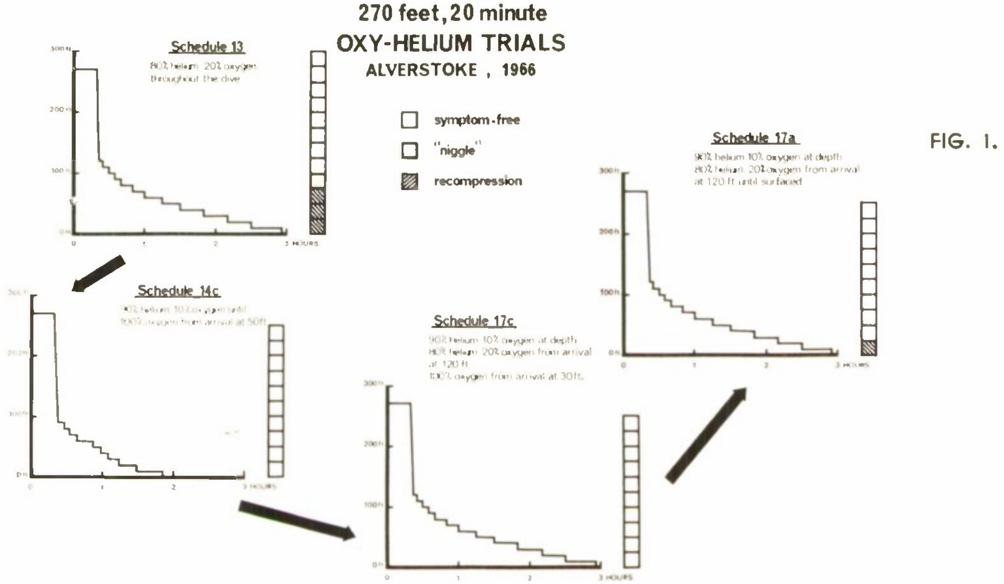


FIG. 1.

is acceptable under certain conditions, nevertheless an upper limit of 0·01 atmospheres (*i.e.* 1% of one atmosphere, surface equivalent) is considered to be a reasonable limit to insist upon. This requires *an efficient scrubber*, the design of which presents some problems in an atmosphere which must be kept free of electric motors. It also presents the problem of *accurate analysis* because it means that due to the expansion of a sample of gas from, for instance, 600 ft one must be able to analyse accurately 0·05% carbon dioxide. On prolonged decompressions we must also insist upon a controlled environmental temperature because oxy-helium has a very high thermal conductivity and less than 82°F is considered by the divers to be cool. Humidity is therefore another factor which must be controlled and a compromise between man's requirement and the efficient scrubbing of CO_2, aims to achieve a relative humidity of around 75%.

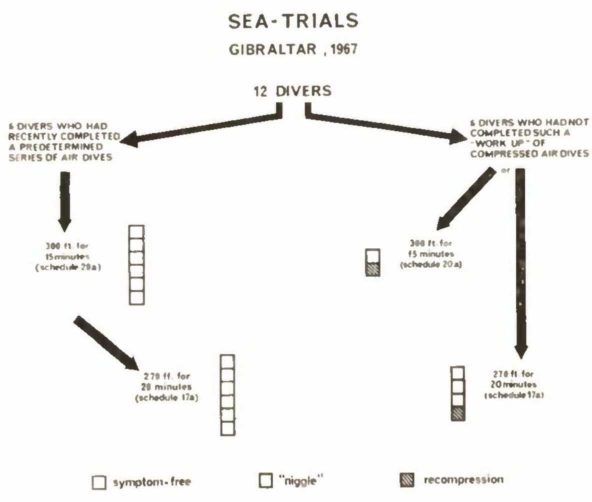


FIG. 2.

Decompression Sickness

Contributory Factors. The design of decompression schedules has already been described and mention has been made of the inevitable incidence of decompression sickness on all dives below about three or four hundred feet. There are also some factors which are believed to influence this incidence and, of course, the estimate of depth must be accurate and the supervisor must adhere to the decompression table selected. The significance of the different factors which affect the safety of decompression schedules is illustrated in Fig. 1. Thus a three hour decompression from a 270 ft, 20 minute dive gave a 30% incidence of bends. By changing the various factors such as work-load, gas mixtures, water temperature and "work-up" it was possible to decompress from the same exposure quite safely on a two hour schedule. Then, on another three hour schedule from the same exposure but using oxygen on the shallow stops, there was again no case of decompression sickness. The final dive of the group of four, 17a, shows the same schedule as was used originally, 13, in fact with a slightly greater partial pressure of inert gas, and only one bend out of 10 dives. The results show that variation of these other factors can affect the success of a given decompression time-course. Similar dives were

taken to sea (Fig. 2) and six divers who had a predetermined "work-up" of air dives had only one incident in 12 dives, whereas six other divers, who had not done the "work-up" but who were subjected to the same conditions in the water, all had some kind of trouble. It is important to remind you that no matter how good any table, the variation between different divers is so great that there is inevitably a very small incidence of decompression sickness on every table.

Long Term Effects of Decompression. About aseptic bone necrosis we know little. From compressed air workers it is known to be more common in those who have been treated for decompression sickness than for those who have not. The incidence of bone necrosis in those who are deep sea divers is not yet known.

Treatment of Acute Decompression Sickness. If decompression sickness occurs then it is necessary to recompress the diver in order to shrink the size of the bubble causing the lesion and to bring the diver back to the surface very slowly in order to give the body time to get rid of the excess inert gas. The treatment must be thorough and the depth of recompression must be to at least the depth of complete relief of symptoms. Adequate treatment should ensure that the diver returns to the surface 100% fit. There are a number of cases, not of Royal Navy divers, in whom treatment has been inadequate and who now suffer from permanent paralysis or other damage. The correct treatment of decompression sickness is therefore very important but to-day we shall consider only the basic requirements of recompression therapy. If the bend begins on the surface the patient is recompressed with compressed air, breathing either the compressed air in the chamber or oxygen from a mask. The maximum depth which this is normally taken to is 165 ft although on occasions 230 ft have been used quite successfully. However occasionally such depths are inadequate to secure a complete cure and there are occasions when one would like to take the diver deeper. Compressed air is no longer suitable because it is toxic at greater depths. Therefore, for decompression sickness following deep dives, as well as for those cases of decompression sickness that may arise during the decompression while the diver is still on oxy-helium from his original dive, divers occasionally need to be recompressed breathing oxy-helium. One can breathe oxy-helium from a mask while sitting in the compressed air environment but 300 ft is considered to be the limit of this. This is because the mask cannot be tolerated for more than a few hours and because a patient with labyrinthine decompression sickness may vomit and therefore be unable to breathe from his mask. It is essential to be able to recompress the diver in a chamber at the surface to at least the depth of his original dive. This is the minimum requirement because there have been occasions when the diver has had to be recompressed to depths considerably in excess of his original dive, for instance, 450 ft depth of relief has followed a 400 ft dive.

Again with deep recompression therapy there is the need for complete and accurate *control of the oxy-helium atmosphere* within the chamber and the need for closed circuit television to supervise the diver. There is also the need for the recompression chamber or deck chamber and the submersible chamber to be able to withstand the maximum pressure to which the diver has been subjected.

Sea Trials of New Diving Tables. It is because of the risks of severe cases of decompression sickness that we must be meticulous about the careful trials of all proposed new decompression tables. It is the convention in the Royal Navy that we will accept a dive for testing in the sea only when 10 individuals have completed that dive successfully in a dry chamber or preferably in the wet section of a pressure chamber. The sample of 10 individuals is accepted as the minimum number only because of the difficulty in allocating men and time to this task. At least 30 divers are needed to achieve an answer that is going to be statistically significant and even with this number, biological variation is such that the results might still be inconclusive. On completion of the compression chamber trials the new tables are taken for trials at sea, and again at least 10 individuals must dive successfully on each selected dive of the table. These trial dives are very carefully supervised, making certain that the depths are accurately recorded, that the diver works to a certain physical standard, that the diver has fulfilled certain conditions of pre-dive "work-up". Nearly always it is found, for reasons which are not wholly understood, that trials which have been successful in the laboratory may give an unacceptedly high incidence of decompression sickness in the sea. It is for this reason that we insist that all new decompression tables must be tested not only in the laboratory but also *in the sea* before being released for operational use. It is also important that not only for trial dives but also for operational oxy-helium dives that a suitable recompression chamber, as already defined, is available.

THE STATUS OF DEEP DIVING

S. Williams, R.N.S.S.
Admiralty Experimental Diving Unit

The Royal Navy has carried out experimental deep dives to 600 ft in the sea on several occasions.

For dives as deep as this, a submersible chamber is used to lower the divers to the working depth. During the lowering, oxy-helium mixture is passed into the chamber via a hosepipe from the surface and this prevents the entry of water and provides a breathable atmosphere for the divers. (Air is narcotic at these pressures).

The chamber is little more than an ordinary diving bell when used in this way and forms a kind of haven from which the divers work while underwater. The R.N. chamber differs from a diving bell in that a door in the bottom can be closed to seal the chamber and retain the internal pressure while the external pressure is lowered. This allows the divers to be brought back to the surface under pressure where controlled decompression down to atmospheric pressure can be carried out. The internal pressure of the chamber must be lowered in this regulated manner (known as a decompression schedule) if decompression sickness is to be avoided.

However, from deep dives the time for decompression will be many hours, often more than 24 so that some degree of comfort for the divers is important. The submersible chamber is therefore designed to be coupled to a larger chamber on the surface into which the divers transfer when the pressures have been equalized. Such a system is known as T.U.P. (Transfer under pressure).

The equipment used by the Royal Navy which is installed in H.M.S. *Reclaim* was the first of this kind and was designed for use to a depth of 300 ft. When used at greater depths it is therefore not possible to surface from the maximum depth but instead, some decompression has to be carried out in the sea until the 300 ft level is reached. The bottom door of the submersible chamber can then be closed and the chamber raised to the surface in the intended manner.

Extending the use of the equipment in this way at one time seemed perfectly acceptable because the time involved in the sea stops (as decompression stages are called) was not particularly long. However, on one occasion during a 600 ft trial dive, a diver developed decompression sickness just after transfering inboard at near the maximum pressure of the surface chamber. The usual cure for decompression sickness is recompression to a greater depth, but this was impossible in the existing chamber as its pressure rating would have been exceeded. There was no alternative but to put the diver back into the submersible chamber and lower him into the sea. He was eventually cured at 450 ft.

Because of this experience a rule has been established that surface chambers must be stressed for pressures equal to the depth of the deepest dive in the sea. Also, because of this experience an attempt at an 800 ft dive was abandoned. It was considered that the risk was now unacceptable, particularly in view of the fact that the diver at 450 ft in the sea was quite beyond the reach of direct medical aid.

It will be appreciated that this type of diving is not without its strains and anxieties for all concerned. Quite apart from the uncertain outcome of the decompression trial itself there are other factors.

Suppose, for example, a 20-minute dive is being carried out to test a new schedule, and because of some mechanical failure in the equipment the divers cannot be brought up until, say 30 minutes have elapsed. What decompression schedule should now be used in order to bring the divers safely back to atmospheric pressure ?

In all probability no tried and tested schedule will exist. In experimental work this situation is inevitable but for practical diving one would like to have sets of tables covering a wide range of depths and times in increments of, say, 5 ft and five minutes.

Present indications are that it may be many years before such an ideal state is realized.

This is due to the large cost in time and manpower required to test and prove each schedule.

TABLE I

Summary of Sea Dives using Oxy-Helium Breathing Mixtures completed from H.M.S. *Reclaim* from May 1962 to June 1965

NORWAY—MAY 1962	
300 ft in 13 minutes	18
TENERIFE—JANUARY/FEBRUARY 1963	
300 ft in 13 minutes	36
400 ft for 10/14 minutes	14
450 ft for 14½ minutes	6
TENERIFE—NOVEMBER/DECEMBER 1963	
300 ft for 16 minutes	18
400 ft for 14/16 minutes	22
500 ft for 15/16 minutes	14
LE LAVENDOU (TOULON)—APRIL/JUNE 1965	
450 ft for 1 hour	10
600 ft for ½ hour	14
600 ft for 1 hour	4
Total number of dives	156

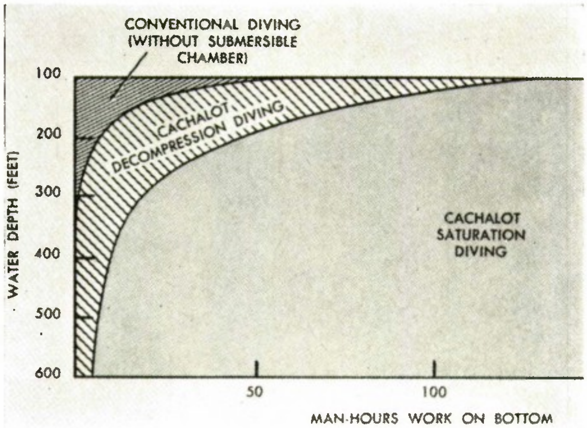
Table I is a summary of the number of experimental sea dives carried out from H.M.S. *Reclaim* in four separate periods each of approximately six weeks. Each of these periods was preceded by as much as one year's work in the laboratory before schedules were even considered ready for sea testing. The series is probably the most comprehensive ever carried out at sea and shows an obvious thoroughness by the repetition in the 300 ft dives in the earlier series until satisfaction was obtained.

Because of the difficulties, and in particular, the lack of a comprehensive set of decompression tables, a type of diving has been developed which, to some extent, short circuits the problems. This is what has become known as saturation diving.

In saturation diving the diver remains under pressure for a very long period by ordinary standards. This period could be days or even weeks. The term saturation diving is appropriate because, after a certain time under pressure, the diver's body ceases to absorb any more gas. It has, in fact, already taken up the maximum amount possible—hence—saturation.

This time may be anything from 4 to 24 hours, depending on the composition of the gas mixture being breathed. Estimates vary to some extent.

A particular form of saturation diving has been developed by the very large American company—Westinghouse. Their method is called the Cachelot system. The equipment for this system differs little in principle from that in H.M.S. *Reclaim*. There is as before a submersible compression chamber, with a crane or derrick system for raising and lowering it, plus a large compression chamber on deck to which the divers transfer.



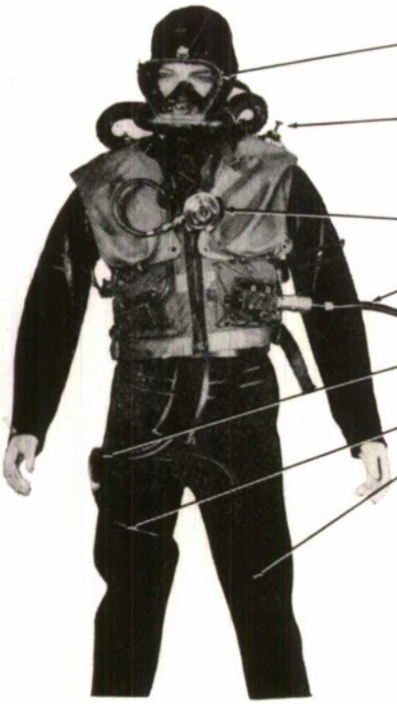
Westinghouse Saturation Diving.

However, once inside their deck chamber the divers remain under pressure and are not decompressed. They may have come up for a meal, for a rest or for a night's sleep but sooner or later they will re-enter their submersible chamber and descend to their diving task once more. This may go on for a week or so—or until the diving job is completed. Only then will decompression begin.

The time for this may well be long, but even so, it will often be only a fraction of the useful dive time rather than the many multiples of short period diving. The question naturally arises as to the economics of this system. Westinghouse state that in their view, saturation diving is economic from a depth of 100 ft when the task might involve 120 hours of work, to a task of perhaps four or five hours at 600 ft.

However the economics is only one consideration. It is the flexibility of the system that will commend it to practical divers. The very idea that divers can go down and come up as and when necessary without having to adhere to a rigid time table must remove much of the inherent anxiety suffered by supervisors of diving operations.

Of interest is the breathing apparatus used in the Cachelot system. This is an adaptation of a U.S.N. breathing apparatus which is itself based on the same principle as some R.N. equipment. In this apparatus gas mixture is metered to the diver on a constant mass basis utilizing the



Breathing apparatus used in the Cachelot System.

property of small orifices when supplied at constant pressure in giving this type of flow. Such an apparatus, usually described as " semi-closed circuit " is reasonably economical in the use of gas mixture—an important consideration when helium is being used.

To make the best use of the divers it is necessary to keep them warm otherwise their working time could be severely limited by cold—taking away all the advantages of the Cachelot system.

In this case the diver is kept warm by hot water which is piped from the submersible chamber to his special suit.

The actual Cachelot chamber is much like any other, but during a remarkable series of dives performed with it in the Gulf of Mexico, salvaging oil production platforms sunk in a hurricane at a depth of 240 ft, 3,600 man hours of diving were carried out in only 15 weeks.

There were 289 descents of the submersible chamber and only 18 decompressions. Evidently the Westinghouse divers spend a week under pressure before being relieved. The longest dive during this operation was six hours.

In saturation diving of this kind it is, of course, possible to make excursions to greater depths than that to which one is saturated.

Operating in this manner, in June of last year, divers living at 350 ft in their Cachelot chamber made a one-hour excursion to 600 ft.

If the impression given is that deep diving is a matter of bigger and more expensive pressure chambers this would be largely correct. So much so that a gathering of boilermakers would be positively enthusiastic.

As an example of modern development in expensive chambers there is *Purisima*. This is really two chambers in one. The upper part is intended to be kept at atmospheric pressure and may house engineers and other observers. It is, in fact, an observation chamber. However, an attendant diver could be housed in this section who could, by pressurizing the chamber, go to the assistance of the working diver who lives in the bottom part.

This idea does not appear to have been an unqualified success because it has given way to another saturation system, the Advance Diving System 4 of Ocean Systems. Ocean Systems is an affiliate of another large American company—Union Carbide. It is interesting to note the active participation in diving by these large American companies.

In August last year, the ADS 4 was used for a well-head completion at 636 ft. The total working time was six hours, out of the 48 which the divers spent under pressure at this depth. The decompression time was six days, which may well be oversafe, but it matters little once the job is done.

The ADS 4 was almost certainly built with the financial aid of the U.S. Navy. A number of them are on order for the Navy and an even bigger version, capable of 850 ft, is under construction.

Table II shows the amount of money which has been budgeted by the U.S. Navy for deep diving. This budget, which was published in 1964, is for a number of items but the one of immediate interest is Item 4.

To date, this adds up to about 6.2 million dollars or roughly 2.5 million (devalued) pounds.

Note, too, the estimate of $1\frac{1}{2}$ years to achieve 600 ft. As previously stated in connection with the two civil companies, 600 ft in the sea was only successfully accomplished last year.

By British standards this is a large sum of money to spend on diving. However, the U.S.N. has other projects in diving to consume this funding.

There is *Sealab 2*, yet another chamber, (Fig. 4) some 57 ft long by 12 ft diameter. This was placed on the seabed and in it, two teams of men lived and worked for 15 days in a depth of just over 200 ft.

This is again saturation diving, but the essential difference from the Cachelot system is obvious. The divers, here, remained on the seabed.

There is a projected *Sealab 3* which may be placed at a depth of 600 ft. Excursions from this

TABLE II

Summary of Deep Submergence Systems Project Finding

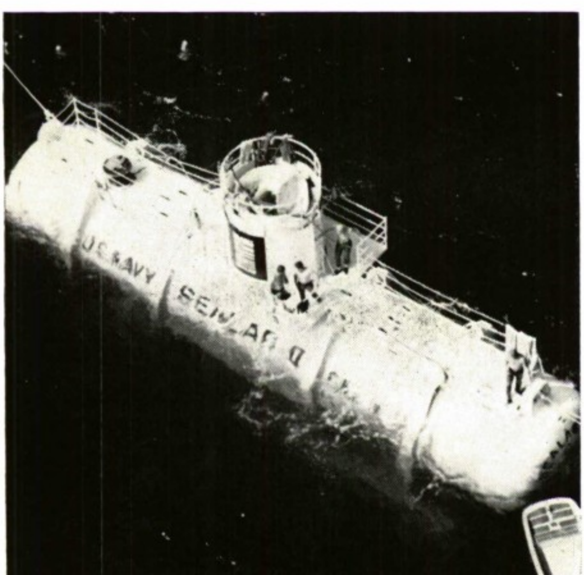
	Capability Item	*Funded by Fiscal Years—Millions*					
		1965	*1966*	*1967*	*1968*	*1969*	*1970*
1.	Submarine Location, Escape and Rescue System. One year, 600 ft, two years 850 ft	1.145	6.550	14.85	10.67	4.895	3.545
2.	(a) Large Object Salvage System. 1,000 tons, five years.	.200	4.08	6.62	5.495	4.07	1.175
	(b) Extended Salvage Depth Capability.	–	1.835	2.565	3.35	3.75	–
3.	Deep Ocean Search, Investigation and Small Object Recovery. To 20,000 ft in 3½ years.	1.32	12.05	24.63	15.81	20.98	18.09
4.	Man-in-the-Sea, Continental Shelf. To 600 ft, 1½ years.	.335	2.735	3.105	1.470	1.470	1.470
	(b) Man-in-the-Sea, Deep Ocean.	–	1.045	1.045	1.45	.200	.200
	Project Office and Special Task Group.	.500					
	Totals:	3.500	28.295	52.820	38.245	35.370	24.485

Grand Project Total $182,715,000 (Subject to Defense and Budget Bureau Adjustments)

depth to 800 or even 1000 ft may take place. A successful simulation excursion to 1000 ft was recently carried out by the U.S.N.

The projected depth 600 ft appears to have been chosen after a demonstration dive to 700 ft was performed by Buhlman and Kellers group in Switzerland.

This fact is mentioned to show that the Americans do not have a monopoly on these long and deep dives. The divers were at depth for 68 hours but, and this is the interesting point, the decompression time taken was 62 hours.



"Sealab II".

This suggests that the Ocean Systems six day decompression was indeed oversafe and that improvements in saturation decompression times are possible.

Also carrying out seabed saturation diving is Cousteau's team. They used a seabed habitat called *Conshelf 3*, a spherical chamber 20 ft in diameter. The accommodation was arranged on two floors inside it. In this chamber six men spent three weeks at 328 ft and excursion dives to 430 ft were carried out. The decompression time taken in this case was four days. There was to have been a *Conshelf 4* experiment last year, when the intended depth was more than 650 ft, but it has apparently been delayed. Seabed habitats are, at present, very much dependent on surface support—particularly

Deep Diver submersible.

for power. They are also static which may be desirable for some purposes, but, in general, for practical diving, mobility is probably more useful. By providing mobility and removing dependence on surface support—yet maintaining saturation diving one has, in fact, invented a special kind of submarine. In this submarine the crew live at atmospheric pressure and provide the domestic services required by the divers who live in their own saturation chambers at seabed pressure. They are thus relieved of many of the chores they have to do for themselves in present day seabed houses, and can concentrate on their diving tasks.

The first diver carrying submarine was the *Perry Cubmarine* now owned by Ocean Systems. It can carry two men in the pressure section and is intended for diving to more than 1000 ft, but is too small for anything but limited duration. Clearly there is a long way to go yet in the development of this type of craft.

This paper is an attempt to give a picture of the state of the art in deep diving, noting the progress that has been made both here and abroad.

The difficulties involved in short period diving have been noted and the way that the saturation technique has been developed to avoid some of them. Saturation is not a universal panacea for diving ills but is now firmly established practice. In 1965 when the last of the sea trials was held in *Reclaim* and when an attempt at an 800 ft dive was abandoned because of the limitation of the equipment, it was decided that what the R.N. needed was a saturation system in the Cachelot manner.

The R.N. has the finest wet and dry chambers in the world for simulated deep diving and it is to be hoped that these will be followed by the finest ship-borne saturation chambers—both in comfort for the divers and for their safety. With such equipment, it will be possible to carry out both types of diving, either short period and of course saturation. This sounds like having the best of both worlds. I hope it is—both for the needs of national defence and for the needs of British Industry.

REQUIREMENTS FOR FUTURE DEEP DIVING RESEARCH

R. P. Common, R.N.S.S.
Admiralty Experimental Diving Unit

Requirements for research may arise from various quarters or a change in operational needs. An advance in physiological knowledge, or a break-through in practical diving capability, anything which permits or requires diving to greater depths or for longer times may reflect on all the other previously stabilized factors in the diving technique.

Previous papers have outlined various aspects of past and present diving requirements and research programmes. Mr. Hempleman (R.N.P.L.) has shown that there are plenty of physiologically based problems for the Royal Naval Physiological Laboratory to solve. For example, why cannot we transfer a satisfactory chamber programme into the sea without getting trouble ? What new problems will arise with saturation diving ? What will limit diving excursions when decompression is no longer the dominant factor ? Are computers or personal monitors a proposition ?

What are the deep diving problems in the engineering field ? Some of these must in fact be solved before the more theoretical aspects can be fully explored in the sea. Mr. Williams (A.E.D.U.) has outlined the equipment required, a submersible compression chamber able to "double" as an observation chamber, and designed to mate to a shipborne "Transfer-under-Pressure" compression chamber. There are other aspects to which attention must be devoted, however. There are requirements for heated diving suits or underwear, power tools, breathing apparatus, improvements to communications and better lighting and closed-circuit television.

It must be very clear by now that the tie between the physiologists, engineers and divers is extremely close. Now let us take a look at the physiological side in greater detail.

Acclimatization

It is well known that men adapt to working under pressure, in the same way as they adjust to other activities, especially if exposed by degrees or are "worked up" as we say. There is scope for an interesting research programme to pinpoint the factors which control the conditioning process. An ideal subject for chamber investigation, with fully controlled conditions and independently altered variables, the trends and interactions being assessed with computer thoroughness. What will happen when we try out our new chamber ideas in the sea ? The "bends" statistics will multiply, therapeutic decompressions will demoralize the subjects, and we are back to simple seamanship again, "The Boffins have come unstuck once more". What is the difference between chamber and sea diving ? Is it temperature, temperament, depth-keeping or time-keeping ? Work pattern or breathing rhythm ? Very soon we shall have to know. Laboratory investigations are so much quicker, safer, cheaper, than full scale sea dives, yet if every programme must be repeated in the sea for lack of correspondence the advantages are illusary.

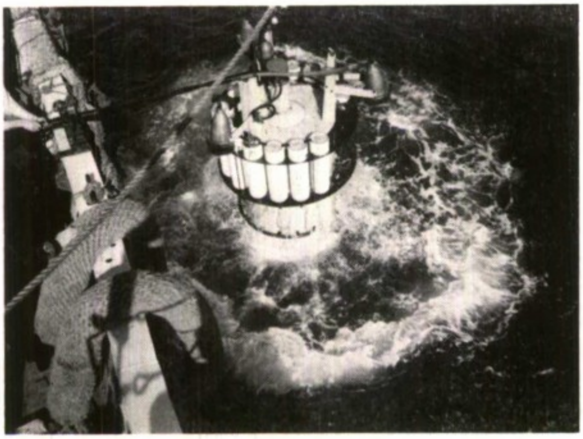
Problems of Saturation Diving

The concept of saturation diving for depths where rapid return to the surface is impossible is most attractive. It by-passes so many nasty problems and really makes sense for deep dives. Four hours at 600 ft, 57 hours to decompress. But persons who saturate easily have taken up all the inert gas possible in five hours at this depth, and can decompress in about 60 hours however long they stay down after saturation. Several people have adopted this technique quite profitably—but what problems will the long term throw up ? Will

prolonged pressure living and chamber confinement disrupt biological patterns? Can hygienic toilet and living conditions be provided and maintained? Will bacterial growth be controlled and will the types of bacteria be different from normal?

What will be the Limits of Excursion?

When the rested man adapted to living under pressure and breathing helium emerges into the sea, how long will he be able to function effectively? What will be his endurance? How deep can he go? We know that at the surface, the deeper we go the higher the bends incidence, but if we are deep stabilized, saturated at 450 or 600 ft, have we greater or less latitude for further deep excursion?



The submerged compression chamber alongside " Reclaim ".

Elimination of Decompression Schedules

The present mathematical derivation of schedules requires a new calculation for every new depth and time combination, with consequent proving. Our recent trials have made it obvious that no schedule with acceptable relationship to working time can be 100% safe and sure for all men at all times. Men differ; a man varies from day to day.

It is interesting to consider the possibility of using some personal monitor which will tell the diver his own state of saturation, and predict the imminence of " bubble " release. Such a monitor could be a boon to an attendant in deciding on variation of decompression routine to suit each particular case. It would add flexibility to what is at present a rather rigid and rigorous programme, sometimes hard to achieve in the sea or under seagoing conditions.

Not so long ago no one had ever proved that a bubble actually existed. It was just a convenient theory. Even now, one is none too sure about the mechanism of bubble growth, propagation and general behaviour. Arguments rage as to the predominance of perfusion or diffusion in the absorption and transport of inert gas, and firm explanations are still as far off as ever.

What of Computers?

Several people have given thought to the design of analogue computers to model man's physiological behaviour when exposed to gas at elevated pressure. The problem is deducing tissue constants for gas absorption. There are a series of theoretical absorption tissues, having different half times for gas uptake or release. There are different theories of the mechanism of uptake. It must always be remembered that a theory is only a theory and not an absolute explanation—only the best fit to what appears to happen. So far, the computers produced are the best fits to the known data, given specified output and input conditions. The most promising computer, designed in the Canadian Institute of Aviation Medicine, fitted all the known schedules and agreed with the recorded cases of failure of these schedules. Unfortunately, as so often happens, the promising hand-made laboratory model originally produced, failed to translate into a production design, and we cannot get one for trial.

Engineering and Material Based Programme for Research and Development

Superficially the equipment required is predictable and a function of the divers' task, dividing into roughly comparatively conventional personal equipment and quite expensive capital installations. In general, in the material field, the Royal Naval Scientific Service Establishments only undertake work to meet agreed " Staff Requirements ", or as aimed research to provide information on which to base such requirement specifications. It is most important that great care be taken in the formulation of these. Much time can be lost trying to satisfy impossible performance specifications included without adequate consideration at the drafting stage. A careful analysis is necessary. What work has the diver to perform? What is his characteristic physical endurance, and his physical limitation? What environmental handicaps exist? Tides, currents, surges, temperature? Must divers' energy be husbanded and output increased by mechanical aids, power tools and vehicles? The importance or relevance of these questions depends entirely on what we want the diver to do. Royal Navy tasks lie mostly in the search and salvage field, seeking lost ships, aircraft, missiles and other equipment which must be found and recovered in quick time, or possibly salvaged with minimum additional damage. The

oil rig diver has perhaps a strenuous physical task of intermittent or short term duration or maybe has to perform a prolonged observational role of lower energy demand. A diver on well-head maintenance will need good physique and endurance and may find power tools of assistance. Some pipeline tasks call for relatively passive, alert, observant inspectors, possibly assisted by a tug or vehicle. Some jobs require jointers, welders, with patience and integrity, and radiographers with unusual combinations of skills.

If the trends reported in Undersea Technology and New Scientist—not to mention "Tomorrow's World", materialize, defence or industrial installations will be emplaced on the bottom in fair profusion and considerable depth. The placing, assembling and maintenance of these pose interesting problems of no small complexity for the seamen, divers, and project engineers concerned. The accurate laying out and lining up, levelling off of foundations and bedplates for such plant presents quite a challenge, not to mention lowering 30 to 40 tons of equipment to marry with bottom fittings to a tolerance of centimetres, at 600 ft.

What are the Essentials?

First, the ability to put the diver on the job. Mr. Williams has described the equipment required to make this possible. Next, effective support to maximize the divers' output and performance.

Breathing Apparatus Requirements

To date, all R.N. diving trials from H.M.S. *Reclaim* have used an open circuit set, a modified Surface Demand Diving Equipment, which is hose supplied, in this case from storage cylinders on the submersible compression chamber via the panel in the chamber. For deep dives where much flow was required, a special Servo demand valve was developed, capable of delivering an exceptional gas flow. This valve is not drawn for production, but has proved very adequate for our trials where open circuit equipment was essential in order to maintain constant gas proportions to eliminate one more variable. It is certain that some such valve will be essential for open circuit sets as depth increases, as long as mouthpiece breathing continues.

This raises the first real future research need. A requirement for a closed circuit mixture set, with external supply, to conserve helium and reduce the storage volume required, thus reducing the size and weight of the submersible compression chamber. A design is in hand for this set under the A.E.D.U's current research programme.

Diver working at depth.

Among other advantages the closed circuit recirculating principle, avoids the loss of a lungful of gas at each breath. The flow requirement is thus greatly reduced. If this asset is coupled with injection into an open face mask, without recourse to a mouthpiece, breathing is considerably eased and a bonus in ease of speaking will also be gained.

Face Masks

There is a fair amount of work being done on face masks, mouthpieces, and ori-nasal masks, in the States. In the U.K., some work is in hand at the Imperial College. There is scope for some co-ordination of this, and a need for a serious study. So far, in the Royal Navy, no existing ori-nasal or open face mask commands any confidence, and nothing at present available would be risked at 600 ft. Certainly some masks have their protagonists, but introduction into service is not yet a proposition.

Communication Research

Provision of open face masks is only part of the story, as we all know. The helium effect on speech is comic at shallow depths. At 600 ft so many frequencies have vanished that articulation in normal language is impossible. Several authorities

have shown interest in the problem but so far the solution appears so complex and expensive, compared with any apparent demand which promises a market, that interest has quickly waned. An American unscrambler is supposed to have overcome the problem and Surgeon Lt. Cdr. Elliott who witnessed this gear in use in Washington early in March 1968, says that it worked to 600 ft. Subject to this aspect, the R.N. have used DUCS, stopping the lifeline cable to the breathing hose. This set has a bone conduction transducer to be independent of face masks, and can work to 800 ft.

Throughwater Communication

This is an ideal which has been a Royal Navy requirement for a long time. There are now several systems available which work moderately well under certain circumstances. Though none are yet likely to perform long at 600 ft without trouble. The set is expensive, approaching £1,000 per outfit. The difficulty from our point of view is compatibility with R.N. mouthpiece breathing apparatus and face masks and the additional complication of wires and attachments. There are other problems, such as choice of frequency. Forty to fifty KHz carrier frequency is popular; it is very free from interference in the water, and makes for a smaller, simpler, circuit, with resultant reduction in price and development cost. On the other hand, for important domestic reasons, the R.N. prefers 7 - 9 KHz as an operating frequency. This is open to interference, and biases development to a larger, more expensive solution. Of course, there are cheap £80 sets on the market. These use actual audio sound into the sea, their range is short, and in our experience are unlikely to have adequate robustness or endurance. They certainly do not possess the energy to work deep.

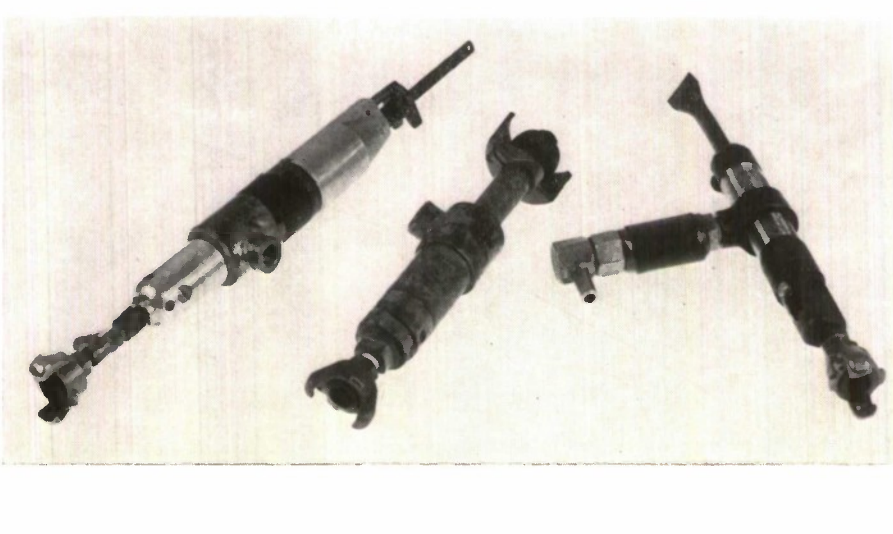
Heating the Diver

The diver breathing helium is losing much heat to the sea. He must be kept as warm and comfortable as the environment will allow. At present the A.E.D.U.'s effort is concentrated on nylon fur underwear, and little formal development is in hand on heated suits, although we are in touch with an American programme, largely with British companies, on this topic.

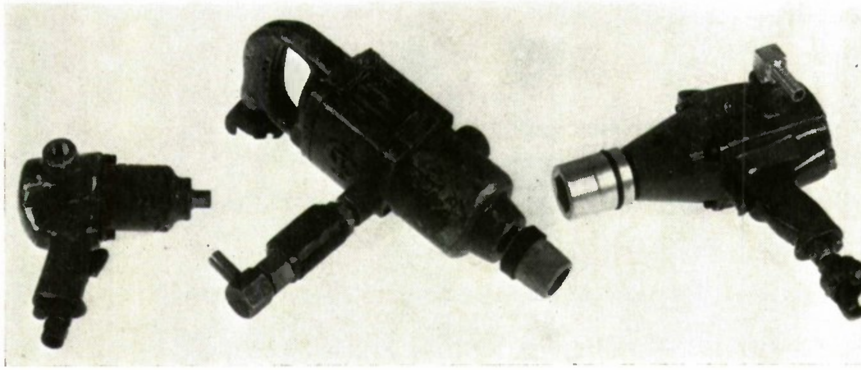
Several techniques are being evaluated on both wet and dry suits including hot water piped through the suit and electric heating elements in the suit. Some promising configurations have evolved, sometimes reflecting aero-space developments, but the problems are control, robustness, and endurance. There are no really effective local energy sources, despite glossy reports and photographs of portable nuclear piles. These have some potentially very lethal properties and have a long way to go. It is possible that fuel cells may eventually make a contribution here, producing heat for the boiler and power for the circulating pump at the same time, and this aspect has been discussed with the Admiralty Materials Laboratory's Fuel Cell Division.

Physical Endurance and Power Tools

When we get the diver to his 600 ft we shall require to design experiments to formally investigate the diver's limitations as to physical endurance and capability. It is to be expected that conservation of divers' resources will become a prime requirement, and work to provide power tools for specific tasks has been in hand for some years. These are used now for work near the surface, although some design variation may be expected to extend their use to the maximum depths. Pneumatic drills, saws, grinders and impact wrenches and nut runners are all now available. An American design of electric drill for full submergence to 800 ft has been developed. Hydraulics are expected to fill a need at these depths also, although we have not yet been able to explore this source of energy.



Pneumatic power tools modified for underwater use. l. to r. file/saw, grinder, weld flux chipper.



Impact wrenches for use underwater.

The tools which we have at present are adaptations of normal surface tools, converted to ensure as little ingress of water as possible. The tool is kept pressurized and the control is on the outlet or exhaust side. It would, of course, be nice to have the tools re-designed to withstand corrosion, but the market has not yet become sufficiently apparent to justify diversion of production capacity to the extent necessary to make an underwater tool a viable proposition in its own right. In fact, we have had difficulty finding one firm sufficiently interested even to try on an experimental basis.

An interesting American development which we hope soon to explore, is the use of liquid gas to power these tools at depth. This technique is claimed to have great advantage over bottle gas, although supply and other complications may vitiate its potential when we get down to cases.

Vehicular Assistance

A corollary to power tools, for future development, is the possibility of a requirement for vehicular assistance for the diver. The highly expensive operation mounted to get him down should not be compromised by requiring the man to swim or walk too far to do his task. He must not be at the mercy of bottom currents. There are problems just the same. What to do with the vehicle when the task is reached, for example. Nevertheless, there is quite a case for vehicles of various levels of complication from simple tugs to submersibles, with diver capability, provided the demand and their performance will justify the undeniably high cost of development.

Conclusion

This Paper has wandered somewhat over physiological and mechanical or material research needs, mixed, perhaps, with gems of information on past and current practice, and future hopes. It will be obvious that the techniques and equipments described are fundamentally oriented to the Royal Navy Defence operational requirements. This is where all our experience lies, and where our responsibility at present directs our attention.

The information is as up-to-date as possible, but things are now moving very fast, and one can be out of date surprisingly quickly. Even as I was writing this Paper, Surgeon Cdr. Elliott was updating me from Washington and several paragraphs had to be re-cast.

It should be apparent that there is a wide range of topics on which work is proceeding, but in any of which worthwhile acceleration of progress is possible, given increased allocation of money and effort, and adequate priority. A prime, and perhaps prior requirement, is to demonstrate the extent of the market if industry is to be attracted to undertake highly expensive, unsponsored development.

Angle impact wrench and angle nut runner for underwater use.

Diving Seminar 1968

IMMEDIATE AND FUTURE REQUIREMENTS OF INDUSTRY

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Introduction

The Construction Industry is continuously growing in size and complexity and has to-day a total annual turnover in the U.K. of £4,000 million of which approximately £150 million is for marine works. The developing North Sea Gas industry is spending a further £50 million annually on exploration and production.

Experienced engineers have in the past designed, planned, constructed and maintained marine projects with the minimum employment of divers. Nevertheless, about £2 million is being spent annualy on diving equipment and services in this country at present, of which nearly 50% is for the North Sea Gas industry. The majority of this diving work in the North Sea is at present carried out by American contractors who are well supplied with the latest information on diving technology.

Clearly diving technology is a very small proportion of Industry's annual turnover, but it is a very vital service which we cannot do without, and will in future, as the oceans are exploited more fully, be in greater demand.

The construction and maintenance of ports, harbours, jetties, coastal protection schemes, cooling water systems, bridge piers, immersed tube tunnels, barrages, effluent outfalls, submarine pipelines are typical of the marine projects undertaken by industry which frequently require diving services.

The cost of support craft, plant and shore establishments on major marine projects can cost over £1,000 per day. An offshore drilling rig in the North Sea prospecting for gas, can, with all its supporting services, cost £8,000 to £10,000 per day to run.

Sometimes the progress of a complete project can depend upon a diver carrying out an allotted task. If he should fail to achieve this on a certain tide, then the weather, tide or some other uncontrollable element may prevent him doing so for several days or possibly weeks. A very expensive delay at £10,000 per day!

Diving technology is, therefore, an important part of marine construction and it is in everyone's interest that this technology is developed to provide greater safety, economy, and reliability.

Working Depths

Most of the work carried out at present in marine civil engineering construction is in water depths of 30 to 90 ft. With the development of larger ships (oil tankers drawing 81 ft of water will be on the high seas later this year) deeper ports will have to be built. Effluent lines discharging into deeper water, immersed tube tunnels in open sea crossings to mention only a few, indicate the requirement in the near future for more work to be undertaken in depths down to 150 ft. It is unlikely that there will be much demand below that depth for civil engineering construction work in the near future.

Diving requirements for the offshore oil industry are to a much greater depth. There is a demand for diving services at present down to 350 ft and in the next three to five years this will certainly go to 600 ft (some of the present North Sea gas concessions are in 660 ft of water) with a possible future requirement to 800 ft.

Type of Work

There are many different tasks that the construction and oil industry require divers to undertake in these various depths of water.

One of these tasks is excavating in materials ranging from soft silts to hard rocks, the latter requiring drilling and blasting, and, therefore, divers with a working knowledge of explosives.

The preparation on the sea bed of foundations for harbour walls, caissons, *etc.* require careful workmanship by divers to ensure that the supported structure is well founded and does not appear above water level looking like a relative of the leaning tower of Pisa.

Marine structures are very varied in their type of construction. Some may require divers to place and screed concrete to set levels, fix reinforcing steel, clean laitance off between concrete pours. Other structures require large concrete-blocks to be placed, an operation which requires careful communication between the diver and the crane driver on the surface.

Pressure grouting is another diving operation requiring clear communication between divers and the surface.

The erection of steel work under water frequently requires steel members to be cut, holes formed and bolted or welded together under water. Sometimes it is easier to make or mark templates underwater and do the necessary cutting, *etc.* on the surface, but frequently divers who are capable of cutting and welding metals underwater are required.

Submarine pipelines sometimes require anchoring to the sea bed, underwater connections made to them, and, after installation, periodic inspections and maintenance, most of which is diving work.

Divers are required to check foundations for scour, clear water intakes of trash and silt, carry out maintenance on drilling rigs, dredgers and support craft while they are kept in use. One must also not forget those not so rare occasions when a vital tool or piece of equipment is dropped overboard; again we look to the diver to retrieve it.

There is not time to mention all the tasks that divers are called upon to carry out in the construction industry. Those mentioned will give some idea of the versatility expected of divers in the industry. They are too often expected to be masters of all trades.

Diver Training

In the past, industry has had a steady supply of standard dress divers from the Royal Navy. Although skin diving equipment is very suitable for inspections, surveys and similar light duties, and is widely used by contractors for general work, for heavy sustained physical work the additional weight, comfort and warmth of the standard dress often makes it the best available equipment.

Many in industry have a preference for training craftsmen to become divers rather than training divers to become craftsmen. As it is understood that the Royal Navy has ceased training standard dress divers, there appears to be little choice in the future. Could Naval facilities and experience be made available to train industry's divers in specialized techniques?

Industry's Diving Requirements

What then are industry's immediate and future requirements in diving technology? These are:

(1) To develop diving techniques to get the diver down to his work location in depths up to 800 ft as quickly as possible and to enable him to stay down until his allotted task is completed.

(2) To bring the diver back to atmospheric pressure as quickly, safely and comfortably as possible.

(3) To equip the diver with tools and equipment which will enable him to perform work of the same quality and in times approaching those he would take on the surface.

Diving Techniques

To achieve these objectives the industry requires more advice and guidance in the more advanced diving techniques.

To enable construction divers to work more economically in the depth ranges 60 to 140 ft more information is required on enriched air techniques which will increase the diver's bottom time and reduce his decompression time.

The present cost of gases and their high transport costs to offshore sites make it essential to economize in their use and use compressed air as much as possible. More advice is needed in the use of air/oxygen systems and on oxygen partial pressure/time factors when using such systems.

The repetitive diving procedure laid down in the Navy Diving Manual is not very convenient when one has to work on the tides. If the recommended stand-off time were decreased to, say, 10 hours, this would frequently enable a diver to get in an extra dive a day.

Industry has many possible applications for saturation diving techniques at all depths. Offshore oil-well sea-bed connections, repairs to the water retaining faces of high dams where draining the impounded area is undesirable, and lengthy construction work in depths greater than 60 ft are only a few examples which come to mind where this technique could be advantageously used.

One dam has already been repaired in America using saturation diving techniques, the time taken being one month against an estimated four months by conventional methods.

The maximum depth of water in which an offshore production structure has been built to date is 340 ft and this is nearing the practical limits for such structures. For production wells in water over 400 ft deep, well-head connections will have to be made either on the sea bed or on submerged structures. Saturation diving techniques will certainly be required for this type of work.

Saturation diving requires facilities for transferring divers, while under pressure, to surface decompression chambers. Units capable of this are available commercially in the U.K. for working depths down to 165 ft and another is being constructed for depths down to 700 ft.

For deep dives, oxy-helium or similar techniques are essential and industry requires more guidance in the use of these techniques. The cost of helium is high, 2s. 6d. cu. ft. It costs approximately £100 per hour, for gas alone, for each diver when diving and decompressing in depths equivalent to 10

atmospheres. Cannot more be done to develop enriched air decompressions, semi-open circuit diving systems and helium recovery systems?

Tools and Equipment

Just a few of the pure diving developments have been mentioned in which industry is interested. Industry employs divers to carry out work, and it therefore requires techniques which will increase the diver's productivity while he is on the bottom.

Frequently, marine construction work is carried out in waters with strong tidal currents, which carry much silt in suspension, thereby causing very poor visibility.

It is almost impossible for a diver to carry out satisfactory inspection tasks in currents exceeding $1\frac{1}{2}$ knots, while to carry out manual work this maximum velocity is nearer 1 knot.

Working time on the bottom can be increased by providing shields to protect the diver from strong currents. For the construction of the cooling water intake foundations for Aberthaw Power Station, a site in the Bristol Channel where the maximum depth of water was 65 ft and currents in excess of 6 knots were recorded, current shields doubled the working time on the bottom. Even then, diving was restricted to 20 minutes at slack water spring tides and 1 hour 40 minutes on neaps. The shields used at Aberthaw consisted of rings 7 ft 6in. high by 30 ft dia. and weighed nearly 30 tons. Lighter shields have been developed and used in the North Sea recently but these provide fixing problems.

Diving tasks carried out in poor visibility are slow and difficult. In the blackest waters, underwater lighting units do not seem to be very affective and industry would welcome improvements in this field. At present, in these conditions, divers work mostly by feel. There is great scope for the development of measuring instruments which could project readings on to the diver's face glass or give audio signals for him to work to. These signals should, if possible, also be transmitted to the surface.

Engineers have in the past always planned underwater construction so as to obtain as many, and as accurate, surface checks on the diver's work as possible. As diving goes deeper and further offshore these checks become more difficult.

When working offshore from a moored craft it is not difficult to establish one's position by the use of laser beams, Decca Hi-Fix or similar systems. It is, however, more difficult to set out positions accurately, both laterally and vertically, on the sea bed beneath a moored ship. In this age ot electronics, have the armed forces any devices which could be utilized to do this type of task?

Similarly, magnetometers and sonar devices to assist divers to locate their working position or find lost tools and equipment would save valuable diving time if available at reasonable cost.

There is only one known manufacturer of underwater magnetometers in this country at present. Could devices used for modern mine detection be adapted and used for this sort of duty?

Better diver-surface communication systems are also required, the greatest need here being for a system which works satisfactorily with oxy-helium diving.

Present underwater welding techniques still do not produce good structural welds. Cutting methods are more developed but systems such as oxy-arc are expensive to operate due to the high cost of electrodes and heavy gas consumption.

There is a great shortage of testing and measuring equipment which can be used under water. When more structural welding is required underwater, those on the surface will want proof of its soundness!

The present tools used by divers are usually adaptations of surface tools. The performance of pneumatic tools, even when fitted with exhausts to the surface, leaves much to be desired, and the maintenance of these tools gives fitters nightmares. Frequently, the only maintenance facility available is a 40-gallon drum of gas oil into which the tools are dropped on completion of a dive.

The cost of getting a diver down to do a job of work justifies equipping him with the most efficient tools. These should be light to handle and designed to require the minimum reaction from the diver and the minimum of maintenance. More development is required in hydraulically operated tools. Electrically operated tools are not really suited to an aquatic environment.

Other Applications

Developments in diving technology have other applications in construction. Dry operations in compressed air (such as tunnelling, caisson sinking, *etc.*) have much in common with diving and much of the research to date on diving could be very relevant to compressed air working.

It is of the utmost importance that the most modern techniques in diving technology are fully understood by all sections of the construction industry. It is of little value the diving contractor knowing the latest techniques and their limitations if the engineer designing the project does not allow for them in his design.

It is also important that the medical profession is kept up-to-date on the latest diving techniques. I wonder how many doctors in this country are familiar with oxy-helium decompression and recompression techniques and are capable of going under pressure if necessary?

Conclusion

The preceding text outlines some of industry's interests and problems in diving technology.

The numerous sections of industry cannot individually afford to undertake all the research and development they require to solve these problems. Furthermore, it would be wasting the Nation's resources for them to duplicate research and development carried out by the various Ministries.

We must therefore have closer co-operation between industry and these Ministries and be willing to share our knowledge and resources if we are to secure a major stake in the world diving industry of the future.

NEW PREMISES FOR ADMIRALTY EXPERIMENTAL DIVING UNIT

The Controller of the Navy, Admiral Sir Horace Law, K.C.B., O.B.E., D.S.C., opened new accommodation costing £100,000 for the Admiralty Experimental Diving Unit in H.M.S. *Vernon*, Portsmouth on Friday, 31st May, 1968. Started in 1946, to support the Royal Navy's Clearance Diving Branch, then developing, the Unit has occupied a variety of temporary accommodation. The new " Permanent Home " reflects the importance attached to modern diving, especially deep diving, by the Ministry of Defence and the Government.

The accommodation comprises offices, laboratories, store rooms, a workshop, compass room, drawing office, accommodation for the Experimental Diving team and associated medical inspection rooms.

The Admiralty Experimental Diving Unit, an outstation of the Admiralty Underwater Weapons Establishment at Portland, is administered by the Director of A.U.W.E., Dr. Ralph Benjamin, as a Royal Naval Scientific Service Research and Development organization, specializing in design of diving equipment and the development of diving techniques for the Ministry of Defence. The Unit is directed at Portsmouth by the Officer-in-Charge, Mr. R. P. Common. Staffed by members of the R.N.S.S., the Unit works closely with the Superintendent of Diving, Commander P. A. White, M.B.E., R.N. and officers and men of the Royal Navy's Diving Branch, to produce all diving equipment required by the Navy and Royal Marine Divers, ranging from wet and dry underwater swimmers' dresses, special underwear, heated suits, and fins or boots, to breathing apparatus, compasses, depth gauges and compression chambers.

A.E.D.U. has supported the Royal Navy's Deep Diving Research Ship H.M.S. *Reclaim* with scientists and essential equipment throughout the Deep Diving Research carried out since 1962. A series of 600 ft. working dives were carried out in the Mediterranean in 1965.

Among the many and varied tasks at present on the Unit programme is a design for completely new compression chamber equipment for H.M.S. RECLAIM, to ensure that Britain shall continue to be one of the world's leaders in the rapidly developing technology of deep diving, so important to both defence and commerce.

The A.E.D.U. is closely in touch with Diving Research enterprises all over the world, sending observers to Commandant J. Cousteau's Pre-Continent Experiments, and to the U.S. Navy's Man-in-the-Sea (or Sealab) experiments in the Pacific.

Co-operative research on diving has been in progress during the last six months with the U.S. Navy's Experimental Diving Unit, teams of U.S. Divers being sent over to the A.E.D.U. Deep Trials Unit where advanced diving trials have been in progress to increase the safety of deeper diving, and contribute to the generally scarce fund of knowledge on man's behaviour during prolonged exposure to elevated pressures. Extremely close co-operation is maintained in this work with the Royal Naval Physiological Laboratories at Alverstoke, whose grounds house the Deep Trials Unit. This advanced equipment will soon be able to test men and equipment under controlled conditions to beyond 1,000 ft in water. The Unit is operated by Lt. Cdr. W. B. Filer, M.B.E., R.N. (Retd.), who is a former diver from H.M.S. RECLAIM and was deputy Superintendent of Diving in the A.E.D.U., until 1963. Two Royal Navy divers, Lt. C. Lafferty and P.O. J. D. Clark are shortly to take part in the U.S. Navy Sealab trials, and A.E.D.U. is supporting these men with some British equipment which will include a heated suit for use during the deep sea dives.

Among the less glamorous but equally important and useful tasks undertaken by A.E.DU. in recent years, has been development of power tools for divers, and assistance to the Navy in establishing techniques for changing propellers on ships whilst afloat, to avoid the necessity of dry docking. These techniques have proved of great value in recent Fleet activities in various parts of the world.

STABILITY AND CONTROL OF SUBMARINES

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PART V. STABILITY AND CONTROL IN THE HORIZONTAL PLANE OF MOTION

Introduction

The stability and control investigations undertaken in this part will use the simplified lateral symmetric equations of motion. It has already been said that these equations are not as representative of the actual motion in the horizontal plane, as the simplified longitudinal equations are of motion in the vertical plane. Nevertheless their study is worthwhile, and this part will follow exactly similar lines to Part IV. Initially the form of the equations will be examined in more detail, and then the non-dimensional equations developed. Criteria for stability will be determined, and performance indices discussed.

The Nature of the Simplified Lateral Symmetric equations of Motion

The lateral symmetric equations were derived in Part III:—

$$(m-Y_{\dot{v}})\dot{v}-vY_v+(mU-Y_r)r=Y(t)$$

$$(I_x-K_{\dot{p}})p-vK_v-pK_p-rK_r+mg\,\overline{BG}\,\phi=K(t)$$

$$(I_z-N_{\dot{r}})r-rN_r-vN_v=N(t) \quad \ldots (29)$$

where $\phi=\int p\,dt$

In tthe above equations the acceleration derivatives are again those representing the added mass and inertias. $(m-Y_{\dot{v}})$ is the virtual mass of the submarine in the transverse plane, and $(I_x-K_{\dot{p}})$, $(I_z-N_{\dot{r}})$ are the virtual inertias about the x and z axes respectively (*viz.* roll and yaw).

Y_v and N_v correspond to Z_w and M_w in the vertical plane, in that they are incidence derivatives. In this case $\frac{v}{U}$ is the sideslip (or side incidence) angle, and Y_v and N_v are the derivatives of the transverse force and yawing moment on the submarine with respect to the sideslip angle. K_v is the rolling moment derivative with respect to the sideslip angle.

Similarly Y_r and N_r correspond to Z_q and M_q in the vertical plane. In this case Y_r and N_r are the transverse force and yawing moment derivatives with respect to angular velocity of yaw r. K_r is the rolling moment derivative with respect to r.

K_p is the rolling moment derivative with respect to the angular velocity of roll p, and it is thus the damping in roll. Y(t), N(t) and K(t) are time dependent external forces and moment, for example, a rudder deflection δr such that it produces no rolling moment would give:—

$$Y(t)=\delta r\ Y_{\delta r}\ ;\ N(t)=\delta r\ N_{\delta r}\ ;\ K(t)=0$$

where $Y_{\delta r}$ $N_{\delta r}$ are the transverse force and yawing moment with respect to δr.

Non-dimensional Simplified Lateral Symmetric Equations

The same non-dimensionalizing method as that used in Part IV is again selected. Forces are divided by $\frac{1}{2}\rho U^2L^2$ and moments by $\frac{1}{2}\rho U^2L^3$

Equations (29) thus become:—

$$(m'-Y_{\dot{v}}')\dot{v}'=v'Y_v'-(m'-Y_r')r'+Y'(\tau)$$

$$(I_x'-K_{\dot{p}}')p'=v'K_v'+p'K_p'+r'K_r'-m'\gamma\int p'd\tau+K'(\tau)$$

$$(I_z'-N_{\dot{r}}')r=r'N_r'+v'N_v'+N'(\tau) \quad \ldots (30)$$

where the dot now denotes differentiation with respect to τ and the dash (or prime) denotes non-dimensional quantities given by the following relations:—

$$v'=\frac{v}{U};\quad p'=\frac{pL}{U};\quad r'=\frac{rL}{U};\quad t=\frac{L}{U}\tau$$

$$m'=\frac{m}{\frac{1}{2}\rho L^3};\quad Y_{\dot v}'=\frac{Y_{\dot v}}{\frac{1}{2}\rho L^3};\quad Y_v=\frac{Y_v}{\frac{1}{2}\rho UL^2};$$

$$Y_r'=\frac{Y_r}{\frac{1}{2}\rho UL^3};\quad Y'(\tau)=\frac{Y(t)}{\frac{1}{2}\rho U^2L^2}$$

$$I_x'=\frac{I_x}{\frac{1}{2}\rho L^5};\quad K_{\dot p}'=\frac{K_{\dot p}}{\frac{1}{2}\rho L^5}\quad K_v'=\frac{K_v}{\frac{1}{2}\rho UL^3};$$

$$K_p'=\frac{K_p}{\frac{1}{2}\rho UL^4};\quad K_r=\frac{K_r}{\frac{1}{2}\rho UL^4}$$

$$\gamma=\frac{g\,\overline{BG}}{U^2};\quad K'(\tau)=\frac{K(t)}{\frac{1}{2}\rho U^2L^3};\quad I_z'=\frac{I_z}{\frac{1}{2}\rho L^5}$$

$$N_{\dot r}'=\frac{N_{\dot r}}{\frac{1}{2}\rho L^5};\quad N_r'=\frac{N_r}{\frac{1}{2}\rho UL^4}$$

$$N_v'=\frac{N_v}{\frac{1}{2}\rho UL^3};\quad N'(\tau)=\frac{N(\tau)}{\frac{1}{2}\rho U^2L^3}$$

The coefficients of equations (30) are now independent of forward speed, with the exception of γ which occurs only in the roll moment equation.

Stability Stick Fixed

In the horizontal plane metacentric stability is necessary for the submerged submarine at rest (or very nearly so) to preserve an upright position. Thus the centre of buoyancy must be above the centre of gravity, and this provides a restoring moment in the pitching plane, and also about the rolling axis. In deriving the simplified lateral symmetric equations it was assumed that any rolling motion would not have any effect on sideslip or yaw, the equations in sideslip and yaw are thus independent of metacentric stability.

If the controls are fixed, following a disturbance the motion of the submarine must satisfy:—

$$(m'-Y_{\dot v}')\dot v'-v'Y'_v+(m'-Y_r')r'=0$$
$$(I_x'-K_{\dot p}')\dot p'-v'K_v'-r'K_r-p'K_p'+m'\gamma\int p'd\tau=0$$
$$(I_z'-N_{\dot r}')\dot r'-r'N_r'-v'N_v'=0 \quad \ldots (31)$$

and the characteristic equation is:—

$$\left[A_1\sigma^2+B_1\sigma+C_1\right]\left[D_1\sigma^2+E_1\sigma+F_1\right]=0 \quad \ldots (32)$$

where $A_1=I_x'-K_{\dot p}'$; $B_1=-K_p'$; $C_1=m\gamma$

$$D_1=(I_z'-N_{\dot r}')(m'-Y_{\dot v}')$$
$$E_1=-\left[(I_z'-N_{\dot r}')Y_v'+(m'-Y_{\dot v}')N_r'\right]$$
$$F_1=(m'-Y_r')N_v'+N_r'Y_v'$$

Equation (32) factorizes into two quadratics because the rolling motion does not affect sideslip or yaw—rolling motion can exist by itself.

The stability of the rolling motion is thus determined by the roots of the quadratic:—

$$(I_x'-K_{\dot p}')\sigma^2-K_p'\sigma+m'\gamma=0 \quad \ldots (33)$$

and for stability the roots must be negative or have negative real parts; this will be satisfied if the coefficients of equation (33) are all of the same sign. $(I_x'-K_{\dot p}')$ the virtual inertia is obviously positive, and thus rolling motion is stable if, and only if:—

$$K_p'<0 \text{ and } m'\gamma>0$$

The first condition is that the rolling motion is damped, a condition not likely to be unsatisfied in any submarine. The second condition is simply the condition for metacentric stability which has already been discussed.

Stability in the directional sense is determined by the roots of the equation:—

$$D_1\sigma^2+E_1\sigma+F_1=0 \quad \ldots (34)$$

and as this is a quadratic the only possibility is straight-line stability. That is, a submarine with straight-line stability after a disturbance will not return to a path parallel to its original direction, but will take up motion along some other straight line. It will be remembered that directional stability in the vertical plane was only achieved by the presence of the metacentric righting moment in the pitching moment equation. In the horizontal plane the metacentric righting moment is in the rolling moment equation, and has no effect on sideslip or yaw.

For equation (34) to have negative roots (or negative real parts) the following conditions must be satisfied:—

$$(I_z'-N_{\dot r}')Y_v'+(m'-Y_{\dot v}')N_r'<0$$
$$(m'-Y_r')N_v'+N_r'Y_v'>0 \quad \ldots (35)$$

The first of these inequalities provides for directional damping, and is usually satisfied. The second is the more important condition for straight line stability. Inequalities (35) would certainly be satisfied if:—

$$Y_v'<0$$
$$N_r'<0$$
$$(m'-Y_r')N_v'+N_r'Y_v'>0 \quad \ldots (36)$$

and these inequalities are seen to be very familiar to those obtained in the vertical plane analysis.

Stick-fixed stability is not necessary in the horizontal plane, although it may be desirable because it is likely that course-keeping will be improved. Should the submarine be unstable these simplified equations of motion would produce a continuing divergence to infinity in response to even the smallest disturbance. The coupling terms K_v' and K_r' would also produce a divergent roll. This of course cannot happen in practice, the unstable vessel would eventually settle at some steady rate of yaw. A measure of this characteristic can be obtained in practice (particularly on ships which are more likely to be unstable than submarines), but as will be shown later the mathematical representation is of considerable complexity.

Control in the Horizontal Plane

The simplified lateral symmetric equations of motion (29) can be written:—

$$\left.\begin{aligned}(m-Y_{\dot v})\dot v - vY_v &= -(mU-Y_r)r+\delta r Y_{\delta r}\\ (I_z-N_{\dot r})\dot r - rN_r &= vN_v+\delta r N_{\delta r}\end{aligned}\right\} \quad \ldots (37)$$

where the dot denotes differentiation with respect to real time, and δr is the angular deflection of the rudder. The rolling moment equation has been omitted because it does not influence sideslip and yaw.

Replacing the coefficients of (37) by non-dimensional coefficients, and assuming $\rho=2$ which is justified in sea-water:—

$$\left.\begin{aligned}\dot v+\alpha_1 v &= \alpha_2 r+\alpha_3\delta r\\ \dot r+\beta_1 r &= \beta_2 v+\beta_3\delta r\end{aligned}\right\} \quad \ldots (38)$$

where $\alpha_1=-\dfrac{Y_v'}{(m'-Y_{\dot v}')}\cdot\dfrac{U}{L}$;

$$\alpha_2=-\frac{(m'-Y_r')}{(m'-Y_{\dot v}')}\cdot U \quad ; \quad \alpha_3=\frac{Y'_{\delta r}U^2}{(m'-Y_{\dot v}')L}$$

$$\beta_1=-\frac{N_r'}{(I_z'-N_{\dot r}')}\cdot\frac{U}{L} \quad ;$$

$$\beta_2=\frac{N_v'}{(I_z'-N_{\dot r}')}\cdot\frac{U}{L^2} \quad ; \quad \beta_3=\frac{N'_{\delta r}}{(I_z'-N_{\dot r}')}\cdot\frac{U^2}{L^2}$$

Transforming equation (38) using Laplace Transform theory:—

$$(s+\alpha_1)\ v(s)=\alpha_2\ r(s)+\alpha_3\delta r(s)$$

$$(s+\beta_1)\ r(s)=\beta_2\ v(s)+\beta_3\delta r(s)$$

and solving for r(s) and v(s):—

$$\frac{r(s)}{\delta r(s)}=\frac{\beta_3 s+(\alpha_1\beta_3+\alpha_3\beta_2)}{s^2+(\alpha_1+\beta_1)s+(\alpha_1\beta_1-\alpha_2\beta_2)} \quad \ldots (39)$$

$$\frac{v(s)}{\delta r(s)}=\frac{\alpha_3 s+(\alpha_3\beta_1+\alpha_2\beta_3)}{s^2+(\alpha_1+\beta_1)s+(\alpha_1\beta_1-\alpha_2\beta_2)} \quad \ldots (40)$$

If the rudder is set to a fixed angle δr_m then:—

$$\delta r(s)=\frac{\delta r_m}{s}$$

and if the denominator of equations (39) and (40) have negative roots or negative real parts (*i.e.* the submarine is stable), then by the final value theorem of Laplace Transform theory as $t\rightarrow\infty$ equation (39) gives:—

$$r \text{ steady state}=\frac{(\alpha_1\beta_3+\alpha_3\beta_2)}{(\alpha_1\beta_1-\alpha_2\beta_2)}\ \delta r_m$$

substituting the original values of the α's and β's:—

$$r \text{ steady state}=\frac{Y_v'Y_{\delta r}'\left[\dfrac{N_v'}{Y_v'}-\dfrac{N_{\delta r}'}{Y\delta r'}\right]}{Y_v'N_r'+N_v'(m'-Y_r')}\cdot\frac{U}{L}\ \delta r_m \quad \ldots (41)$$

Y_v' and N_v' are the non-dimensional force and moment derivatives with respect to sideslip angle, and the ratio $\left|\dfrac{N_v'}{Y_v'}\right|$ gives the non-dimensional location with respect to the centre of gravity of the centre of pressure of the submarine in the transverse plane. This point is sometimes referred to as the trim point (cf. the neutral point in the vertical plane). Similarly $\left|\dfrac{N_{\delta r}'}{Y_{\delta r}'}\right|$ gives the non-dimensional location of the centre of pressure of the rudder. Thus equation (41) shows that if the centre of pressure of the rudder is at the trim point the rudder produces zero steady turning rate. In fact a typical submarine will have a trim point 0·25L forward of the centre of gravity (in a similar position to the neutral point) and hence the most effective rudder location, from the point of view of steady turning rate, will be at the stern, which is its usual location.

The steady state value of the sideslip velocity is given by:—

$$v \text{ steady state}=\frac{-Y_{\delta r}'(m'-Y_r')\left[\dfrac{N_r'}{m'-Y_r'}+\dfrac{N'_{\delta r}}{Y'_{\delta r}}\right]\cdot U\delta r_m}{Y_v'N_r'+N_v'\ (m'-Y_r')} \quad \ldots (42)$$

Thus if the centre of pressure of the rudder was at a point given by:—

$$\frac{N'_{\delta r}}{Y'_{\delta r}}=-\frac{N_r'}{m'-Y_r'}$$

there would be no sideslip in the steady state motion. In a typical submarine the ratio $\frac{N_r'}{m'-Y_r'}$ gives a position 0·3L forward of the centre of gravity, and a rudder at this position just forward of the trim point, even if it were practicable, would be extremely inefficient in producing a rate of turn, as was shown by equation (41).

Re-introducing now the rolling moment equation previously given in equations (29) and now re-written in terms of the angle of roll ϕ:—

$$(I_x-K_{\dot{p}})\ddot{\phi}-\dot{\phi}K_p+mg\,\overline{BG}\,\phi=K_v v+K_r r$$

By similar analysis to that used for the other parameters the steady state angle of roll is given by:—

$$\phi_{\text{steady state}}=\frac{K_r'}{m'g\,\overline{BG}}\cdot\frac{U}{L}\,r_{\text{steady state}}+\frac{K_v'}{m'g\,\overline{BG}}\cdot\frac{U}{L^2}v_{\text{steady state}} \quad \ldots (43)$$

where the steady state values of r and v are given by equations (41) and (42) respectively.

In the previous discussion it was noted that a rudder at the trim point would produce small steady state values of r and v, and hence also small steady state values of roll angle ϕ. Small roll angles are desirable, but not at the expense of turning ability. However, another approach is possible.

In a typical submarine the following relation is approximately true:—

$$\frac{N_v'}{Y_v'}-\frac{N'_{\delta r}}{Y'_{\delta r}}=-\left[\frac{N_r'}{m'-Y_r'}+\frac{N'_{\delta r}}{Y'_{\delta r}}\right]$$

Using equations (41), (42) and (43) it can be seen that ϕ steady state is proportional to $K_r'Y_v' + K_v'(m'-Y_r')$, and even with the rudder in the conventional position at the stern, where it produces the largest steady state rate of turn, it is still possible for the steady state roll to be very small if:—

$$K_r'Y_v'+K_v'(m'-Y_r')=0$$

that is if $$\frac{K_r'}{K_v'}=-\frac{m'-Y_r'}{Y_v'} \quad \ldots (44)$$

It is not unreasonable to assume that the derivatives K_r' and K_v' are almost entirely dependent upon the size and position of the bridge fin, and thus the ratio $\frac{K_r'}{K_v'}$ gives the longitudinal non-dimensional distance of the centre of pressure of the bridge fin from the centre of gravity of the submarine. This is easily deducable from the fact that a sideslip velocity v produces an equivalent angle of incidence of the bridge fin of $\frac{v}{U}$, whereas an angular velocity r produces an equivalent angle of incidence $\frac{rl_F}{U}$ where l_F is the longitudinal distance of the centre of pressure of the bridge fin from the centre of gravity.

$$\text{Thus } \frac{K_r'}{K_v'}=\frac{l_F}{L}$$

Now it is often found that $(m'-Y_r')$ is approximately equal to $-N_v'$ and thus the right hand side of equation (44) becomes the ratio determining the position of the trim point. Hence if the bridge fin is in the vicinity of the trim point equation (44) is satisfied and the steady state roll angle will be small, even with the rudder at the stern. Comparatively small steady state roll angles do not of course preclude the occurrence of much larger roll angles in the transient motion, a lightly damped system overshoots its final steady state by a considerable margin. Roll motion damping is provided by the derivative K_p which is again almost entirely dependent on the bridge fin. Thus another compromise situation has arisen since to a large extent the rolling of a submarine is induced by the presence of the bridge fin (through the action of K_v' and K_r'), and yet the damping is also largely provided by the bridge fin. The ideal solution is one which reduces the initial overshoot or snap-roll angle to a minimum, and an obvious solution was thought to be the removal of the bridge fin altogether. The results of an experiment with a model with bridge fin removed are given in Reference [1]. The principal conclusions of this experiment were that the reductions in snap roll were not quite as dramatic as expected, nevertheless roll angles were much reduced although the turning ability of the submarine was also reduced. The fact that snap roll still occurred indicated that the line of action of the centripetal force did not pass through the centre of gravity.

Performance Indices

Much of the section on performance indices in the vertical plane (Part IV) is also relevant to this section with a slight change in wording. Thus in the assessment of control effectiveness (in this case the rudder) the parameter $\frac{M_{\delta r}}{I_z}$ is of value, particularly in the comparison of the powers of rudders on different submarines. Similarly another index of performance is the non-dimensional time taken to attain a 10° change in heading angle following the application of maximum rudder angle. The overshoot manoeuvre (described in Part IV) is also directly applicable, and can be

extended by repeating the execute angle at each side of the original path and so obtaining a zig-zag manoeuvre. The same parameters as were measured on this manoeuvre in the vertical plane are useful in the assessment of course-changing ability. Again, as for depth-keeping, course-keeping can also be realistically studied by setting up a computer as a simulator, and analyzing the performance of human operators or automatic controls by statistical methods.

Motion in the horizontal plane is, however, different in some noticeable respects from motion in the vertical plane, and further manoeuvres are necessary for the assessment of performance. For instance large changes of heading are often undertaken, and knowledge of turning ability is required for manoeuvring in confined seaways. Thus, of interest are the results of heading changes through large angles (90°, 180° or 360°), the time required, the roll angles and the speed losses are important measurements. As has already been pointed out, however, the simplified equations of motion are not really adequate for the simulation of this latter type of manoeuvre, because the assumption of small disturbances, and no speed change, was made in their derivation. More realistic equations will be dealt with in later pages.

If a submarine is unstable in the horizontal plane its motion is even less amenable to representation by simplified equations, and although instability is not desirable it does sometimes occur in the horizontal plane (Reference [1] quoted two instances). A well-known manoeuvre (the Dieudonné spiral manoeuvre) is undertaken to determine the amount of instability (if any) in the lateral motion, and although it cannot be represented by simplified equations, it will be described herein because it does provide performance indices. This manoeuvre is carried out by starting with some pre-determined rudder angle and measuring the steady rate of turn this produces. The rudder angle is then reduced in increments through the neutral position, to an equal and opposite value on the other side, and then in further increments returned to its original setting. At each rudder position the vessel is allowed sufficient time to settle into a steady rate of turn, and the rate of turn is recorded. The vessel possessing one-to-one correspondence between rudder angle and rate of change of heading will produce a single curve if the rudder angle is plotted against the rate of change of heading. The unstable ship not possessing this characteristic will produce a type of hysteresis curve as shown in Fig. 11. Anywhere within the loop the response of the vessel is indeterminate, and to achieve positive response in a particular direction rudder angles greater than those defined by the width of the loop are always necessary. Clearly a vessel with a loop

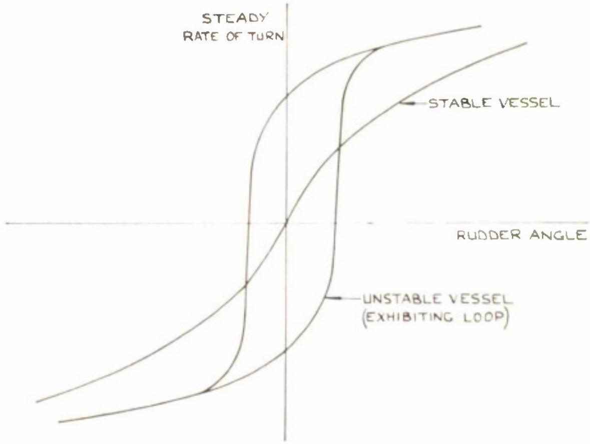

FIG. 11.

of significant width will require excessive use of its rudder to achieve satisfactory control, hence limits have been proposed from time to time, but more particularly with reference to surface ships which are more prone to exhibit this characteristic.

PART VI. THE THEORETICAL ESTIMATION OF DERIVATIVE VALUES

Introduction

In the preceding pages it has been shown that a great deal of information about submarine performance, and stability and control, can be elicited from a study of the simplified equations of motion, despite the fact that many assumptions had to be made in their derivation. The simplified equations were also seen to be quite amenable to solution, but in order to be able to predict probable motions and displacements it is, of course, necessary to have available realistic numerical values of the coefficients of the equations. It would obviously be highly desirable to be able to determine these coefficients in the early stages of design, at which time necessary modifications could easily be made to a design which did not, on the basis of prediction, fulfil the desired requirements. Furthermore, if numerical values could be reliably determined theoretically there would not be a need for elaborate experimental apparatus. With this objective a number of theories have been developed, and some of them are reviewed in this Part.

Between the two world wars, largely because of restrictions placed upon them in other fields, the Germans undertook a great deal of research into

the aerodynamic characteristics of airships, and they were the leaders in the design of these craft. By the beginning of the Second World War airship production had virtually ceased, but the research had direct application to submarines and torpedoes, and during the war the Germans built the greatest fleet of submarines the world has ever seen, with vessels designed for a variety of operational rôles. Some of the relevant work on airships is referred to in this chapter, although the references are, in general, to American reports, which are more easily obtainable.

In recent years high speed aircraft and missiles have developed long slender fuselages with wings of small aspect ratio, and theories for the determination of the aerodynamic forces on such combinations again find application to the study of the forces on a submarine and its control surfaces. Most of these theories are too complex for inclusion in this introductory note, and only brief mention will be made of one or two, sufficient it is hoped to give some idea of the problems involved in the theoretical estimation of derivative values.

Classical Theories—Bare Hull

The derivation of the forces and moments on an ellipsoid moving through an infinite ideal fluid can usually be found in text books on classical hydrodynamics. An early work applying these theories to airship hulls was that of M. M. Munk published in 1924[7]. Munk presented the general theory of the aerodynamic forces on airship hulls, a theory which was used in the study of the forces experienced by the airship *ZR-I*. The airship was considered in the first instance to be without tail fins (*i.e.* bare hull), and proceeding on a straight course at an angle of incidence α_1. The calculated force and moment on the hull should thus give derivatives for the bare hull, Z_w and M_w in the vertical plane, and Y_v and N_v in the horizontal plane. For a body of revolution about the longitudinal axis with no appendanges the derivatives Z_w and M_w are obviously equal to Y_v and N_v respectively. The airship was then assumed to be in a curved path such that the longitudinal axis made an angle α_2 with the tangent to the path, and these calculations provide Z_q and M_q (or Y_r and N_r) for the bare hull. Some of the results obtained are given in the following paragraphs.

For the closed neutrally buoyant body of revolution in straight line motion in the fluid with velocity U and at incidence angle α_1, the total aerodynamic lift on the body is zero. There is however an aerodynamic moment given by:—

$$M=\tfrac{1}{2}\rho U^2(k_z-k_x)\forall\sin 2\alpha_1 \qquad \ldots (45)$$

where $\forall$ is the volume of the body, and the coefficients k_z and k_x are the coefficients of apparent mass. These coefficients k_z and k_x have been calculated by Lamb[5] for ellipsoids of revolution and are given in Table I.

TABLE I

Length/Diameter	k_x	k_z
1·0	0·5	0·5
2·0	0·209	0·702
3·99	0·082	0·860
6·01	0·045	0·918
8·01	0·029	0·945
9·97	0·021	0·960
∞	0	1·0

In the non-dimensional derivative terminology the relation (45) could be written:—

$$M_w' \text{ (bare hull)} = m'(k_z-k_x) \qquad \ldots (46)$$

and since the lift force is zero:—

$$Z_w' \text{ (bare hull)} = 0$$

It can be seen from Table I that for a body with a length to diameter ratio greater than 8, k_z is approximately equal to 1, and k_x is zero. These values for the added masses of a streamlined body of high length to beam ratio were previously noted in Part IV, and for such a body the equation (46) becomes:—

$$M_w' \text{ (bare hull)} = m'$$

Munk also obtained the force distribution along the hull such that the transverse (or lift) force on an element dx is given by:—

$$dZ=\tfrac{1}{2}\rho U^2\frac{dS}{dx}dx\,\sin 2\alpha_1$$

where $\frac{dS}{dx}$ is the rate of change of cross-sectional area.

On a closed body of revolution this distribution gives equal and opposite forces on the fore and aft sections of the body, producing zero total aerodynamic force, but a resultant moment (in fact a couple).

For the body rotating with constant angular velocity such that its longitudinal axis makes an angle of incidence α_2 with the tangent to the path, Munk found that again there is no resultant force. The moment is similar to that obtained above being given by:—

$$M=\tfrac{1}{2}\rho U^2(k_z-k_x)\forall\sin 2\alpha_2$$

although the distribution of force along the body is different in this case.

If the vessel is in a turn with zero incidence angle the non-dimensional derivations are clearly:—

$Z_q' = 0 \quad ; \quad M_q' = 0$

It is obvious that the assumption of an ideal fluid leads to quite serious discrepancies, since it is well-known that an airship hull at an angle of incidence will be subject to a lift force, albeit small. The "Munk moment" has also been found to over-estimate (often by some 30 per cent) the moment measured by experimental methods. Munk himself observed these facts, and suggested that the estimation of the lift acting over the rear half of the hull was the most in error due to the undoubted presence of vortices near the hull.

Von Karman[8] conducted similar investigations on the bare hull of the *ZR-III*, assuming equivalent circular cross-sections at all stations. His theoretical methods involved the use of sources and sinks, or doublets along the axis of symmetry. The results were a little closer to experimental values than those of Munk, but there was still a discrepancy at the stern. Von Karman claimed to have obtained better agreement by assuming the existence of a vortex trail, as in aerofoil theory, and calculating the effect of the vortices on the lift. However, he also concluded that the method was not capable of general application.

Undoubtedly these classical theories give some indication of the source of the forces and moments on a hull, but the fact that agreement was not obtained with experimental results, even for the simple case of a body of revolution with no appendages, is somewhat disappointing.

In theoretical investigations of this nature terminology developed in the study of aerofoils is frequently used, and a brief digression will be made at this point to introduce, in particular the lift and drag coefficients. The resultant force on an aerofoil of a given shape at a particular angle of incidence depends mainly on the density ρ of the surrounding fluid, the relative velocity U of the aerofoil and the fluid, and a typical length l. The combination $l^2 \rho U^2$ has the dimensions of a force, and thus the lift and drag of an aerofoil are defined as follows:—

$$L = \frac{1}{2}\rho U^2 l^2 \, C_L$$

$$D = \frac{1}{2}\rho U^2 l^2 \, C_D$$

The factor of one-half is introduced for convenience, since $\frac{1}{2}\rho U^2$ is the dynamic pressure, and l^2 is usually replaced by a typical area S, often in aerofoil theory the projected area of the aerofoil. C_L and C_D are the coefficients of lift and drag

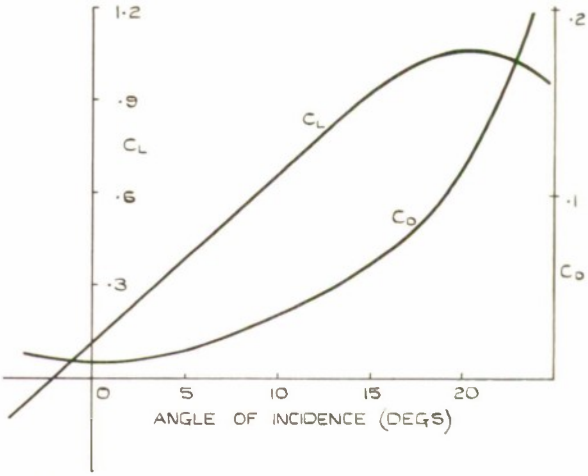

FIG. 12.

respectively, and are functions of the angle of incidence, the variation of C_L and C_D for a typical aerofoil are shown in Fig. 12.

The theoretical slope of the curve of lift coefficient against angle of incidence for the two dimensional aerofoil (*i.e.* of infinite span) is 2π per radian.

Reverting now to the discussion of the forces experienced by a bare hull, a further attempt to produce a more realistic theory is given in Reference [9]. In this reference the lift coefficient for a blunt-based body as determined by potential theory is given, to this term is added a contribution due to viscosity. Thus the lift coefficient is:—

$$C_L = 2(k_z - k_x)\left(\frac{S_b}{A}\right)\alpha + \eta C_{D_c}\left(\frac{A_p}{A}\right)\alpha^2$$

where S_b is the area of the blunt base, A is a reference area, A_p is the planform area, C_{D_c} is the drag coefficient experienced by a circular cylinder of diameter equal to the beam of the hull, and η is the ratio of the drag coefficient of a circular cylinder of finite length to that of infinite length. For most applications C_{D_c} is approximately equal to 1·2, and η is given in Table II.

TABLE II

Length/Diameter	1	3	5	7	9	11	13
η	0·53	0·59	0·62	0·65	0·67	0·69	0·71

Clearly for a closed body of revolution $S_b = 0$ and the first term of the above equation for the lift coefficient, which is the contribution determined by potential theory, is zero. The lift coefficient

calculated in this manner compared quite favourably with experimental results obtained on two airships, the U.S.S. *Akron* and the *R-101*. Submarines are usually closed bodies of revolution and thus the lift coefficient is given by:—

$$C_L = \eta C_{D_c}\left(\frac{A\rho}{A}\right)\alpha^2$$

which is a second order term dependent on α^2.

Semi-Empirical Methods—Bare Hull

In another attempt to devize a more accurate method of predicting the force distribution on a bare airship hull, Upson and Klikoff[10] introduced a modification to Munk's original theory. However, if the results of using this method are compared with experimental data obtained on the U.S.S. *Akron*[11], it is, in fact, found that near the stern the method of Upson and Klikoff is not much better than the classical theories. Further investigations about this time showed that Von Karman's assumption of a trailing vortex system was quite justified, and that the bare hull did have a trailing system similar to that of an aerofoil of low aspect ratio. Unfortunately, of course, Von Karman had already indicated that a method based on this assumption was not suitable for general application.

Methods that have been quite extensively applied in work on torpedoes and more recently surface ships[12], were first proposed by Albring in a report published in Germany in 1944. One method requires that in the first instance the lift coefficient of the hull is determined experimentally. This means, in effect, the experimental determination of Z_w. Ideal fluid theory indicated that $Z_w=0$, and thus Albring concluded that any non-zero value of Z_w measured experimentally must be due to the viscosity of the fluid. Furthermore the non-zero value of Z_w must arise as a result of the fluid flow over the stern being in some way modified. It was seen in the last section that the ideal fluid theory predicted a force distribution in one direction over the forward part of the hull, and an equal and opposite force distribution over the stern part of the hull. Albring assumed that as the viscous forces which produce the non-zero values of Z_w mainly affect the flow over the rearward part of the hull, the resultant of these viscous forces must pass through the centre of pressure of the force distribution over the rearward part of the hull, as determined by classical theory (*e.g.* Munk). Thus, if it is assumed that the centre of pressure of the force distribution over the rearward part of the hull, determined by classical theories, is a distance x_o from the centre of gravity, the experimentally determined force Z_w acts through this point and thus:—

$$M_w' = m'(k_z - k_x) - \frac{x_o}{L} Z_w' \quad \ldots (47)$$

where x_o is negative for distances aft of the centre of gravity.

In other words the moment due to incidence angle is the Munk moment (46) modified by the measured force Z_w acting through the point distant x_o from the centre of gravity.

Since ideal fluid theory showed that the body in a curved path, with its longitudinal axis at an angle α to the tangent to the path, experienced similar total forces and moments to the body in a straight path at an angle of incidence α, Albring assumed that in the curved path the body would experience equivalent viscous forces to those obtained experimentally in the straight path. He also assumed that they would act through the same point distant x_o from the centre of gravity. Thus if the body is rotating with angular velocity q, the force on the hull will be given by:—

$$Z = -Z_w \cdot \frac{qx_o}{U}$$

since $-\frac{qx_o}{U}$ is the equivalent incidence angle at $x=x_o$.

In non-dimensional terms the derivative Z_q' is given by:—

$$Z_q' = -\frac{x_o}{L} Z_w' \quad \ldots (48)$$

and similar reasoning gives:—

$$M_q' = \left(\frac{x_o}{L}\right)^2 Z_w' \quad \ldots (49)$$

Having obtained Z_w' experimentally it is thus possible to obtain values for M_w', Z_q', and M_q' by using equations (47), (48) and (49), but despite the fact that these formulae have found a number of applications, they are not particularly reliable in their application to hull forms. A further development of this method is the experimental determination of both Z_w and M_w. If these two values are available then the point of application of the viscous forces, x_o, can be calculated without recourse to the classical theories. This value of x_o can then be used to determine values of the curvature derivatives Z_q' and M_q'. Albring also showed that in many cases the numerical value of x_o is equal to approximately one-half of the prismatic coefficient. The prismatic coefficient is the ratio of the volume of displacement of a vessel to the volume of the circumscribing solid having a constant section equal to the maximum immersed cross-section, and a length equal to the overall length of the vessel.

T. R. F. Nonweiler in some unpublished work attempted a more detailed estimation of the effect

of the boundary layer over the stern of the hull of a submarine, relying once more on experimental results obtained with airship models. The formulae he arrived at apply only in turbulent flow and are as follows:—

$$Z_w' = -\frac{1{\cdot}5}{(Re)^{\frac{1}{5}}}\left(\frac{D_o}{L}\right)$$

$$M_w' = \frac{1}{L}\int_0^{x_{crit}} f(x)\,dx + \left[\frac{x_{crit}-\lambda}{L}\right] Z_w'$$

$$Z_q' = \left[\frac{x_{crit}-\lambda}{L}\right] Z_w'$$

$$M_q' = \frac{1}{L}\int_0^{x_{crit}} \left[\frac{x-\lambda}{L}\right] f(x)\,dx + \left[\frac{x_{crit}-\lambda}{L}\right]^2 Z_w'$$

where D_o is the maximum diameter of the hull

Re is the Reynolds number (see Part VII paragraph 2).

L is the length of the hull

$$f(x) = 2\eta_1\pi\left[\frac{z_{max}}{L}\right]^2$$

$2z_{max}$ is the maximum beam of the hull at any point distant x from the bow.

x is the distance from the bow

x_{crit} is the value of x at which $f(x) = -Z_w'$

λ is the distance of the centre of gravity from the bow

η_2 is a factor which varies along the hull depending upon the cross-section, it can be calculated and an average value used. In fact $\eta_1 = 1{\cdot}0$ for an elliptical or circular cross-section, and most modern submarines are approximately this shape. η_1 will most surely be between 0·9 and 1·0.

$x = x_{crit}$ is referred to by Nonweiler as the plane of wake-shedding, a self-descriptive term, and there are two values of x for which $f(x) = -Z_w'$ the rearmost position is the one appropriate to these calculations. It is assumed that no lift is developed aft of the plane of wake-shedding.

It will be seen that agreement is obtained between Nonweiler's and Albring's formulae if, among other things, the plane of wake shedding coincides with the point of application of the viscous forces assumed by Albring.

Empirical Methods—Bare Hull

In his paper to the R.I.N.A. in 1961[6] Nonweiler said that as yet there is no accurate theoretical assessment of the hydrodynamic coefficients available. Certainly it must already be apparent that the comparison of theoretical and experimental results for even the simple case of the bare hull has not been particularly encouraging. However because experimental facilities have had to be continually used to check the theories as they were developed, a great many results have been accumulated for airships and submarines. Thus if one has to make an assessment of derivative values without conducting more model tests it is often possible to find results of a previous investigation on a similar hull form. Of course, most experiments have been conducted with hull forms which are bodies of revolution, or nearly so, and if one is considering any other form it is unlikely that previous results will be found; it is also unlikely that any theoretical method will prove adequate.

As a check against experimental results therefore seems necessary it is hardly worthwhile using the more complex theoretical methods, the following empirical relations will probably give an order of magnitude.

$$Z_w' = -\frac{1{\cdot}5}{(Re)^{\frac{1}{5}}}\left(\frac{D_o}{L}\right) \quad \text{or } Z_w' = -0{\cdot}57\,m'$$

$$M_w' = m' + \tfrac{1}{2}Z_w'$$

$$Z_q' = -0{\cdot}08m'$$

$$M_q' = \tfrac{1}{2}Z_q'$$

These formulae only apply in the case of a body which approximates to a surface of revolution, and has a major to minor axis ratio greater than, say, 6 : 1. The first formula given for Z_w' is the one derived by Nonweiler and does not apply in laminar flow, that is if $Re < 10^6$ or thereabouts.

Effect of the Appendages

The derivative values required for the prediction of the performance of a submarine must not, of course, be only bare hull derivatives, but must include the effect of fins, appendages and propeller. First attempts at this more complex problem were again made with respect to airships, and, in particular, Munk having calculated the aerodynamic moment when the ship has an angle of incidence to the direction of motion (equation (45)) then determined the size of fin required to produce an equal and opposite moment. He again assumed an ideal fluid, and used the two-dimensional lift slope for the fin (*viz.* 2π), although he did make a correction for the proximity of the fin to the hull by assuming the effective fin area to include that part of the hull in between the fins. Albring also considered the effects of tail fins, and assumed that his formulae (equations (47), (48) and (49)) still applied, although the value of Z_w' used therein should include the fin effect.

The derivation of the theoretical slope of the curve of lift coefficient against angle of incidence can be found in Reference [13]. In fact, the average slope is shown by experiment to be less than the theoretical value of 2π per radian (used by Munk), due to the departure of the flow from ideal form. For a good aerofoil section a value of six per radian is more normal. This is, of course, the two-dimensional value; there are theories for the case of the more realistic three-dimensional or finite wing, neglecting for the moment the effects of interference between a fin (or wing) and the hull. The first of these is the so-called lifting line method, and the simplest solution is for the case where the aerodynamic load distribution across the span is assumed to vary elliptically. The analysis can be found in Reference[13] where it is also pointed out that if the angle of incidence is assumed constant across the span (*i.e.* the aerofoil is untwisted), the lifting line technique requires that the aerofoil planform is also elliptical. For such a load distribution the induced drag is also a minimum. The lift slope is given by:—

$$\frac{C_L}{\alpha} = \frac{2\pi}{1+\frac{2}{A}} \qquad \ldots (50)$$

where A is the aspect ratio, defined as the span divided by the mean chord.

Thus the normal force on a horizontal fin of elliptical planform, when subject to a normal velocity w is given by:—

$$Z = -\frac{1}{2}\rho S U^2 \left(\frac{2\pi}{1+\frac{2}{A}}\right)\frac{w}{U}$$

for small disturbances. In derivative notation this relation reduces to:—

$$(Z_w')_{fin} = -\frac{S}{L^2}\left(\frac{2\pi}{1+\frac{2}{A}}\right) \qquad \ldots (51)$$

where S is the area of the fin.

It is possible to use the lifting line method for other load distributions, and hence other planforms; the results are a little more complex but are not found to differ greatly from those for the elliptical wing. For instance the results for the elliptical and rectangular load distributions are compared in Table III.

TABLE III

Aspect ratio	∞	10	8	6	4	2
Lift slope, elliptic	6·28	5·24	5·02	4·70	4·18	3·14
Lift slope, rectangular	6·28	5·04	4·84	4·54	4·04	3·04

The lifting line theory is most noticeably unreliable when it is applied to wings of small aspect ratio, and a number of investigations have made use of the modifications due to Weinig[14], who considered particularly the lift and drag of wings with small span. Weinig indicated that his results would have special significance in the calculation of the lift of the fuselage, and of the lift and drag of the vertical tail surfaces of an aircraft. The lift coefficient derived by Weinig is:—

$$\frac{2\pi \tanh\left(\dfrac{1}{\dfrac{A}{2}+\dfrac{2\sin\alpha}{\pi}}\right)}{1+\tanh\left(\dfrac{1}{\dfrac{A}{2}+\dfrac{2\sin\alpha}{\pi}}\right)}\cdot\left(\frac{A}{2}+\frac{2\sin\alpha}{\pi}\right)\tan\alpha \qquad \ldots (52)$$

where α is the angle of incidence of an isolated wing of aspect ratio A.

There are also a number of lifting surface theories that give the spanwise and chordwise pressure distributions on a wing or fin. To quote one as an example, the method due to Falkner[15] assumes that the lifting surface can be represented by a number of discrete horseshoe vortices, and the pressure distribution determined from the summation of the effects of these vortices. Present day computing techniques permit the consideration of large numbers of vortices, although it has never been demonstrated that calculations involving large numbers necessarily lead to a more accurate solution.

However, none of the above theories consider the effect of wing-body interference, although it was noted that for the fins at the stern of an airship Munk assumed the effective area to include that portion of the hull in between diametrically opposite fins. In fact for a fin attached to a flat surface with very small clearance, it can be assumed that the effective fin area includes the reflection of the fin in the plane surface. Unfortunately in practice the fins are often attached to a very much curved surface, particularly those at the stern of a submarine. The problem of the influence of the body or fuselage on the wings or fins is discussed in Reference [16], and to quote one of the simplest results given therein, consider the case of a wing attached to an infinitely long cylindrical body. For the case of a rectangular distribution of lift across the span of the wing, the total lift of the combination is given by:—

$$L = \rho U \Gamma 2b\left(1 - \frac{R^2}{b^2 - e^2}\right) \qquad \ldots (53)$$

where Γ is the circulation about the wing of

span 2b, and the body is of diameter 2R. e is the height of the wing above the axis of the body.

Another result indicates that if the distribution of lift across the span of the wing is elliptical then the induced drag is given by:—

$$D_i = \frac{1}{2} \frac{L^2}{\rho U^2 \pi} \frac{b^2}{(b^2 - R^2)^2} \quad \ldots (54)$$

where L is the associated lift.

In Reference [13] the induced drag for the isolated wing with elliptical load distribution is given by:—

$$D_i = \frac{L^2}{2\rho U^2 \pi} \cdot \frac{1}{b_e^2}$$

and comparing this result with equation (54) it is seen that the effective span of a wing-body combination of wing span 2b is given by:—

$$2b_e = 2b \left(1 - \frac{R^2}{b^2}\right)$$

In other words the method used by Munk probably over-estimates the ability of the hull as a lift producing agent, as it appears that the influence of the hull is to reduce the effective span of the wing.

There are also many other, usually more complicated, theories that have been developed for the study of aircraft wing-body combinations, which could possibly be applied to submarines. For instance, Bryson[17] developed a method for slender missiles with wing-body and vertical tail configurations, although the restriction is made that the after end of the fuselage and all trailing edges lie in a plane perpendicular to the longitudinal axis. It is possible that this method could be extended to cover configurations more like a submarine, where trailing edges occur ahead of Bryson's base plane, by considering the effect of vorticity shed from the trailing edges as shown by Jones[18]. It is obvious that calculations of this nature are fairly complex, and the question must arise as to whether the end justifies the means.

Again in some unpublished work Nonweiler has extended his theories for the bare hull to include hull-fin combinations. He considers the cases of a fin situated either ahead of, or behind, the plane of wake-shedding, and draws on aircraft theories to calculate the lift of the hull-fin combination. For the fin behind the plane of wake-shedding the cross-section of the body is assumed to be increased by the boundary layer, the thickness of which has also to be estimated. Having calculated $(Z_w')_{fin}$ the contribution to the other derivatives due to the fin are:—

$$\left.\begin{aligned} (M_w')_{fin} &= -(Z_w')_{fin} \cdot \frac{x}{L} \\ (Z_q')_{fin} &= -(Z_w')_{fin} \cdot \frac{x}{L} \\ (M_q')_{fin} &= (Z_w')_{fin} \left(\frac{x}{L}\right)^2 \end{aligned}\right\} \quad \ldots (55)$$

Albring also has attacked this problem in a similar manner to his method for the bare hull, he indicates that his formulae for the bare hull (equations (47), (48), (49)) can be modified if instead of the assumption made for x_0, values of x_0 are found for the hull-fin configuration under consideration. Alternatively, for a small fin distant x from the centre of gravity, Albring assumes a value for $(Z_w')_{fin}$—presumably determined experimentally—and uses the above relations (55) to determine the other fin derivatives. Clearly for this method, as for Nonweiler's, the derivative values for each fin or appendage must be obtained and added to the bare hull derivatives.

Unfortunately none of these theories takes into account the effect of the propeller on the forces experienced by surfaces within its range of influence, and the surfaces at the stern of a submarine certainly come within this category. Another disadvantage is the complexity of most of the fin-body configuration theories. Furthermore, experimental results indicate that the assumption used by Munk, Albring and Nonweiler that the transverse force in a curved path is proportional to the angle of attack at the centre of pressure due to rotation is not satisfactory. On these grounds, one hesitates to recommend formulae that will give derivatives for the complete submarine of even the right order of magnitude. However, it is suggested that some idea of the hydrodynamic forces on the appendages can be obtained by use of the simplest formulae, lifting line or Weinig, to calculate $(Z_w')_{fin}$, and the contributions to the other derivatives obtained by using equations (55). Some confirmation of this approach can be obtained from Reference [12], where it is indicated that an appraisal of experimental results for torpedoes shows the assumption of non-interference between fin and body to be reasonable. In which case it is sufficient to calculate the effect of an isolated fin or appendage by any suitable method and add the results to those obtained for the bare hull.

PART VII. EXPERIMENTAL DETERMINATION OF DERIVATIVE VALUES

Introduction

Experimental determination of the forces and moments on airship hulls was first undertaken to check the accuracy of the theoretical predictions by classical methods. Following the realization that the experimental results differed noticeably from their predicted values, there has been continued development of both theoretical and experimental methods using increasingly refined techniques. In the field of submarine design the situation remains unchanged; despite the efforts of a number of first class theoreticians the predictions of the hydrodynamic forces on a submerged submarine are still unreliable. Consequently there is now almost complete dependence on experimental methods for obtaining derivative values for a particular submarine design. This chapter will take the form of a somewhat brief resumé of experimental techniques, the emphasis being on the principles involved rather than actual details of experiments.

There are basically two types of experiment that can be conducted, one involving free-running models, and the other using captive models. Free-running is a self-descriptive term, and the models are often radio controlled, although in certain cases the "fishing line" technique is still used, whereby the model is connected to its control station by a light line which should have no effect upon the motion. Various specific manoeuvres are performed with models of this first type, most of which have been mentioned in previous chapters, for example the overshoot, zig-zag, turning circle, and Dieudonné spiral manoeuvres. In the past most of these experiments have been conducted on the surface or at periscope depth, but development of techniques and the construction of larger facilities has enabled the range to be extended to include a limited number of experiments in the vertical plane, and with completely submerged submarines. However, the results of experiments of this type are of limited value, they are useful from the point of view of ship-model correlation, but provide little information on the relation between performance and design characteristics.

One of the purposes of this note is to show that the motion of a submarine can be adequately represented by equations whose coefficients are effectively the forces and moments experienced by the submarine in certain conditions. The magnitude of these forces and moments depends directly on the design of the vessel, and hence a direct correspondence between design and performance is available if it is possible to determine the forces and moments. For experimental determination captive models are required, models which are towed through the water in a variety of attitudes, so that the hydrodynamic forces and moments can be measured.

Scale Effect

Whatever the type of experiment being conducted a significant problem is the scale effect, when working with models certain conditions must be fulfilled in order that the results can be applied to the full-scale ship. For the majority of experiments one would expect that a prime consideration would be that the model be geometrically similar to the prototype, with scale reproduction of all design details. This is generally the case, although the use of curved models will be discussed in later paragraphs. Strictly speaking scale reproduction should also include surface roughness, but this would be an extremely difficult undertaking.

If a submarine is completely immersed in water then a typical force acting on the vessel will depend on the relative velocity U, the size of the vessel (specified by a typical linear dimension such as the length L), the density of the fluid ρ, the kinematic viscosity $\nu(\frac{\mu}{\rho}=\nu)$, and, if near the surface where waves may be formed, g the acceleration due to gravity. Thus a typical force F is given by:—

$$F=K\,L^a\,U^b\,\rho^c\,\nu^d\,g^e \quad \ldots (56)$$

where the following are the dimensions of the factors:—

F—typical force	$-MLT^{-2}$
K—constant	—non-dimensional
L—typical length	$-L$
U—velocity	$-LT^{-1}$
ρ—mass density	$-ML^{-3}$
ν—kinematic viscosity	$-L^2T^{-1}$
g—acceleration due to gravity	$-LT^{-2}$

Inserting the dimensions in (56) and equating the indices of L, M, and T produces:—

$$1 = a + b - 3c + 2d + e$$
$$1 = c$$
$$-2 = -b - d - 2e$$

or by reduction:—

$$a = 2 - d + e$$
$$b = 2 - d - 2e$$
$$c = 1$$

and substituting back in (56) and re-arranging:—

$$F = K\ L^2U^2\rho \left(\frac{\nu}{LU}\right)^d \quad \left(\frac{gL}{U^2}\right)^e$$

and thus for strict dynamical similarity at different scales the ratios $\frac{\nu}{LU}$ and $\frac{gL}{U^2}$ should be invariant. $\frac{LU}{\nu}$ is known as the Reynolds Number, and $\frac{U}{\sqrt{gL}}$ as the Froude Number. It is obvious that, for the same fluid at the same temperature, to satisfy the invariance of the Reynolds number the ratio of model speed to full-scale speed must be the same as the ratio of their linear dimensions. Thus in experiments with a one-tenth scale model the corresponding model speed should be ten times that of the full-scale submarine. However, in order to make the Froude number invariant the model speed should be that of the full-scale submarine divided by the square root of the scale. That is, the one-tenth scale model should be run at a speed approximately one-third that of the full-scale. Clearly it is physically impossible to satisfy both of these requirements, and some compromise is necessary for experiments conducted on or near the surface. For present purposes only deeply submerged submarines are being considered, and Froude number is of little consequence; the effect of any difference in Reynolds Number is much more important.

The Reynolds Number Effect

It is obviously practically impossible to undertake all experiments with scale models at the correct Reynolds Number; to simulate a speed of 20 knots with a one-twentieth scale model would require a towing speed of 400 knots. Consequently the majority of experiments are carried out at a somewhat low Reynolds Number, and the effect on the validity of the results is to some extent still unknown. However, it is generally accepted that quite large variations in the Reynolds Number can be tolerated, provided certain precautions are taken.

In the consideration of a body totally immersed in a fluid, an important effect associated with the Reynolds Number is the variation in the flow pattern around the body. At low Reynolds Number boundary layer separation usually takes place while the flow is still laminar, above a certain critical Reynolds number the transition to turbulent flow in the boundary layer occurs before separation, and the separation point moves aft along the body. Various estimates for this critical Reynolds Number have been given, but it probably lies in the region $6 \times 10^6 - 10^7$, and model tests should be run at a Reynolds Number greater than this critical value. This would ensure a more realistic flow pattern, and for a typical submarine a model 15 ft long would require a towing speed of at least five knots to achieve a Reynolds Number of 10^7.

A great deal has been learned about almost all the topics discussed in this note from work undertaken on airships and aircraft; this applies equally in the experimental field. Experiments in wind-tunnels have provided a lot of useful information, and workers in these facilities at one time thought that stimulating a turbulent flow in the working section would produce effects similar to those of increased Reynolds Number. If the body is bluff or is similar to an aerofoil with maximum thickness well forward this may be the case, since at high Reynolds Number such a body will have its transition point (from laminar to turbulent flow) well forward. Testing such a body at low Reynolds Number in almost laminar flow may have the undesirable effect of inducing laminar separation near the nose. If however at the same low Reynolds Number the flow is made turbulent, then the transition to turbulent flow in the boundary layer may take place ahead of the point where previously laminar separation took place, and so the effective flow would be roughly equivalent to that at a higher Reynolds Number. On the other hand, if the body is not bluff but of low-drag form, then there will be an appreciable extent of laminar boundary layer even at high Reynolds Number. Any artificial increase in the turbulence of the flow may only have the effect of bringing the transition point forwards, and so reducing the similarity between model and full scale.

" Water-tunnels " are used by hydrodynamicists, and artificial turbulence could be induced if required. However " water-tunnels " are not normally used in the measurement of forces and moments on models; they are usually employed in the study of propellers, hence they are usually referred to as cavitation tunnels. The measurement of hydrodynamic forces and moments is usually undertaken on models towed along a large tank, and the turbulence of the flow is not under the control of the experimenter to the same extent. In the first experiment each day the effective flow

may be nearly laminar; after that it is not possible to wait too long for the water to settle, and on subsequent experiments there is likely to be some turbulence present. When this point has been neglected it has been known to produce "inexplicable " discrepancies in experimental results.

Another approach to this same problem involves the experimenter in having some fore-knowledge of the location of the transition point from laminar to turbulent flow in the boundary layer. If the position of the transition point is known the turbulent boundary layer could be artificially stimulated by using wires, sanded areas, or studs on the model at the appropriate point. This method, although extensively used, is open to criticism on the grounds that even if the turbulence is stimulated in the right place, it is not necessarily the same as naturally induced transition.

In using a towing tank it would appear that it is not easy to determine realistic corrections for Reynolds Number effect. Experiments should be carried out at a Reynolds Number above the critical value for transition, and if low-drag bodies are being studied the water should be allowed to become as non-turbulent as possible between experiments. Having taken these precautions, a number of experiments could be undertaken at a range of Reynolds Number (as high as possible), and some indication obtained of the likely trend in the direction of the full-scale Reynolds Number.

Experimental Determination of Derivatives with Respect to a Linear Velocity

The experimental facility most widely used for ship and submarine model experiments is the long towing tank, of which a number have been built in many countries. A model is towed along the tank usually by a carriage running on rails at either side of the tank, and early experiments were chiefly concerned with measuring the resistances of models. Resistance and propulsion experiments are still regularly undertaken, but at this stage in this note only the simplified equations of motion are being considered, and the " null-speed " concept used in the development of these equations requires no knowledge of resistance and propulsion coefficients.

As the model is towed through the water at a fixed attitude, it is subject to hydrodynamic forces and moments, and there is a variety of methods of measuring these forces. Usually the model is attached to its towing strut (or struts) by stiff flexures, and the deformation of the flexures measured, or the relative movement of one end of a flexure relative to the other determined. The force necessary to produce a given deformation or relative movement, is previously determined by a calibration using a force of known value; this calibration is used during the experiment to relate the deformation obtained to the probable hydrodynamic force causing it. To obtain moments the forces are measured at two positions in the model, most successfully by having twin towing struts about one-third, or one-half, of the model length apart. The forces measured at these two positions can be resolved into a moment about the centre of gravity.

Although for research purposes experiments are carried out with bare hulls, or various combinations of appendages in order to determine their effect, for present purposes knowledge of the forces experienced by the complete vessel, as designed, is required. Thus the propeller must be included as it has quite an appreciable effect on the flow, particularly in modern submarines where it is situated just aft of the rudders and after hydroplanes. The propeller is usually driven by a small motor inside the model, and some care has to be taken in setting a realistically equivalent rate of revolutions. Slightly different procedures are sometimes adopted. In some tanks the propeller revolutions are adjusted during a particular run along the tank so that the measured drag force is zero. This method is considered by some to simulate self-propulsion, but it is possible that the effect of the propeller might be over-emphasized. An alternative procedure is to calculate the frictional resistance of the hull on the basis of scale and adjust the propeller revolutions to overcome this amount of resistance. Adoption of this procedure usually results in some residual drag, but it could be that the effect of the propeller on the flow around the hull is more realistically simulated.

The non-dimensional derivatives with respect to linear velocities, in the simplified equations, are Z_w', M_w', Y_v', and N_v' and their physical significance was described in Parts IV and V. To determine Z_w' and M_w' for a complete submarine, its model is suspended from the towing carriage in an upright position, and for a particular towing speed the propeller revolutions adjusted accordingly. The control surfaces are set to zero deflection, and several runs are made along the tank, each one at a different angle of incidence which can usually be set by positioning of the towing struts. During each run the vertical forces will reach a steady state value, and by measuring them the total vertical hydrodynamic force and pitching moment can be determined. At noted in Part IV the slope of the plot of the force (or moment) against the angle of incidence can be used to obtain the derivative Z_w' (or M_w') since for small angles of incidence $\tan^{-1}\frac{w}{U} = \frac{w}{U}$. The angles

of incidence used in the experiment should thus not be too large to make this assumption invalid. If the experiment is repeated at different towing speeds similar values of Z_w' and M_w' should be obtained, because these are non-dimensional derivatives, and should be speed independent. Any marked variation in the derivative values obtained at various speeds would probably indicate some dependence on Reynolds Number, but provided the towing speed is high enough (greater than the critical Reynolds Number) the dependence on the Reynolds Number should be very small. The plot of the force (or moment) against angle of incidence will not necessarily pass through the origin, because the submarine will most probably not be symmetrical. It is often found in practice that to maintain the neutrally buoyant, balanced submarine in a straight and level path small steady state displacements of the control surfaces are required. These displacements are known as the balance angles, and their effect is to nullify the non-zero hydrodynamic forces experienced by the submarine even though it is in level trim.

The above method also applies in the determination of Y_v' and N_v'; in this case it is common practice to suspend the submarine model on its side, in this way the angles of side incidence are obtained in an exactly similar manner by raising or lowering the struts.

Without going into detail it can be seen that the control surface derivatives Z'_δ $Y'_{\delta r}$ *etc.* can also be obtained using the above method. Having obtained values of these derivatives it is possible using the equations of motion and the values of the hydrodynamic forces on the level submarine to obtain estimates of the balance angles. Alternatively it is possible by trial and error, towing the model along the tank with various small control surface angles until such a combination is found that there are no resultant hydrodynamic forces on the submarine in level trim.

Experimental Determination of Derivatives with Respect to Angular Velocity

In the determination of the so-called rotary derivatives once again the methods first employed had been developed in the study of airships[19]. Curved models were constructed such that if they were towed in a straight path each section had the appropriate equivalent incidence to that which the straight model would have had if towed in a curved path. Using this method the derivatives Z_q', M_q', Y_r', N_r' can be obtained in the towing tank. Obviously this method is unrealistic particularly when it is required to fit a propeller to the model, and the models are expensive and difficult to construct (more than one is required, since one model only corresponds to one particular condition). However the method is still in use in establishments where improved techniques have yet to be developed.

The most realistic way to obtain the rotary or curvature derivatives is to tow the straight models in a curved path. A number of large tanks have now been built in which it is possible to conduct experiments of this nature. A rotating arm is used, models can be attached at various radii, and on rotation of the arm the models are towed in a large circular basin. Various angular velocities and radii of attachment are used and by measuring the hydrodynamic forces the derivatives can be calculated. Obviously with the model towed in an upright position the derivatives Y_r', N_r' are obtained, and to obtain Z_q', M_q' the model must be towed on its side. The models and instrumentation required in these experiments on the rotating arm are exactly similar to those required in the long towing tank.

Experimental Determination of Derivatives using the Oscillator Mechanism

In the methods described above particular velocities were applied and the actual hydrodynamic forces measured; these are termed direct methods. The technique using an oscillator mechanism is an indirect procedure, because having measured the hydrodynamic forces on a model for a specific forced motion, it is assumed that the motion of the model satisfies certain equations. These equations are then solved to obtain values of the hydrodynamic derivatives. The equations of motion which are used are usually the simplified versions developed in Part III. Despite its indirect approach this method has been used quite extensively in both aircraft and submarine investigations. It is of particular value to establishments not possessing a rotating arm basin in that rotary derivatives can be obtained in the more common long towing tank. Furthermore, it is the only method so far used to obtain experimental values of the acceleration derivatives, values of these derivatives previously being estimated by consideration of the classical theories for ellipsoids of revolution in ideal fluids. The extensive development of the oscillator mechanism into a refined experimental process is due to Gertler and Goodman[20], and the following description is taken from their publications on this subject.

The submarine model is suspended from the towing carriage of the long towing tank. It is suspended by two struts each of which can be oscillated sinusoidally in the vertical plane while the model is being towed through the water. The phases and amplitudes of the oscillations of the struts can be adjusted, and it is possible for the

model to be in pure pitching motion, pure heaving motion, or perhaps a combination of pitching and heaving.

When the mechanism has been adjusted so that the model is in pure pitching motion the angle of attack α at the centre of gravity of the model is zero. Thus the velocily component w and the acceleration component $\dot{w}$ along the z-axis are both zero. If the motion of the forward strut is given by:—

$$z_1 = a_1 \sin \omega t$$

then the motion of the after strut with respect to the mid-position of the forward strut is given by:—

$$z_2 = a_2 \sin (\omega t - \phi_s)$$

where a_1, a_2 are the amplitudes of the oscillations, and ϕ_s is the required phase difference between the struts in order to obtain pure pitching motion.

The pitch angle θ of the submarine will be given by:—

$$\theta = \frac{z_2 - z_1}{b}$$

where b is the distance between the struts.

If the amplitude of oscillation of the struts is made equal, that is $a_1 = a_2$

$$\theta = -\frac{2a}{b} \sin \frac{\phi_s}{2} \left(\cos \left(\omega t - \frac{\phi_s}{2}\right) \right)$$

$$\dot{\theta} = q = -\left(\omega \frac{2a}{b} \sin \frac{\phi_s}{2} \right) \left(-\sin \left(\omega t - \frac{\phi_s}{2}\right) \right)$$

$$\ddot{\theta} = q = \omega^2 \frac{2a}{b} \frac{\sin \phi_s}{2} \left(\cos \left(\omega t - \frac{\phi_s}{2}\right) \right)$$

where $\frac{2a}{b} \frac{\sin \phi_s}{2}$ is the maximum amplitude of θ in the pure pitching motion.

Earlier it was noted that when the submarine is in level trim there are often measurable values of hydrodynamic force and moment due to its asymmetry. If the submarine is oscillated about the level trim position, with control surfaces set in a neutral position, then these non-zero terms should be taken into account. Using the simplified form of the equations of motion developed in Part III the force and moment experienced by the submarine for motion in the vertical plane can be written as follows:—

$$Z = Z_{\dot{q}} q + (\tfrac{1}{2}\rho L^3 Z_q' + m) qU + (Z_{\dot{w}} - m)\dot{w} + \tfrac{1}{2}\rho L^2 U Z_w' w + Z_*$$

$$M = (M_{\dot{q}} - I_y) q + \tfrac{1}{2}\rho L^4 U M_q' q + M_\theta \theta + M_{\dot{w}} w + \tfrac{1}{2}\rho L^3 U M_w' w + M_* \quad \ldots (57)$$

where Z_* and M_* are the force and moment on the submarine in level trim, and the metacentric righting moment has been denoted M_θ (Presumably the balance angles could have been set on the control surfaces, thus nullifying Z_* and M_*, and then for oscillation about the level trim position these terms could have been omitted from the above equations).

Substituting for θ, $\dot{\theta}$ and $\ddot{\theta}$ in equations (57) and considering pure pitching motion ($w = \dot{w} = o$):—

$$Z = \omega^2 \left(\frac{2a}{b} \frac{\sin \phi_s}{2} \right) Z_{\dot{q}} \cos \left(\omega t - \frac{\phi_s}{2}\right) - \omega U \left(\frac{2a}{b} \frac{\sin \phi_s}{2} \right) \left(\tfrac{1}{2}\rho L^3 Z_q' + m_m \right) \left(-\sin \left(\omega t - \frac{\phi_s}{2}\right) \right) + Z_* \quad \ldots (58)$$

$$M = \omega^2 \left(\frac{2a}{b} \frac{\sin \phi_s}{2} \right) \left(M_{\dot{q}} - I_{ym} \right) \cos \left(\omega t - \frac{\phi_s}{2}\right) - \omega U \left(\frac{2a}{b} \frac{\sin \phi_s}{2} \right) \left(\tfrac{1}{2}\rho L^4 M_q' \right) \left(-\sin\left(\omega t - \frac{\phi_s}{2}\right) \right) - \left(\frac{2a}{b} \sin \frac{\phi_s}{2} \right) \left(M_{\theta m} \cos \left(\omega t - \frac{\phi_s}{2}\right) \right) + M_* \quad \ldots (59)$$

where the suffix m applied to terms involving physical dimensions implies that they are model dimensions.

If it is assumed that the motion of the model satisfies the simplified equations of motion (*i.e.* the indirect approach) then the hydrodynamic force and moment on the model in its progress through the water will be given by equations (58) and (59). In an experiment it is usual for the forces to be measured at the bottom of each strut, and since it has been assumed that $a_1 = a_2$, the struts must be symmetrically placed with respect to the centre of gravity, and the following relations will apply:—

$$Z = Z_1 + Z_2$$

and $M = \frac{b}{2} \left(Z_2 - Z_1 \right)$

where Z_1 and Z_2 are the forces measured at the two strut positions.

Referring again to equations (58) and (59) the in-phase and quadrature components of force and moment can be written as:—

$$(Z_1)_{in} + (Z_2)_{in} = \omega^2 \left(\frac{2a}{b} \sin \frac{\phi_s}{2} \right) Z_{\dot{q}}$$

$$(Z_1)_{out} + (Z_2)_{out} = -\omega U \left(\frac{2a}{b} \sin \frac{\phi_s}{2} \right) (\tfrac{1}{2}\rho L^3 Z_q' + m_m)$$

$$\frac{b}{2}\left((Z_2)_{in}-(Z_1)_{in}\right)=\omega^2\left(\frac{2a}{b}\sin\frac{\phi_s}{2}\right)\left(M_{\dot{q}}-I_{ym}\right)-M_{\theta m}\frac{2a}{b}\sin\frac{\phi_s}{2}$$

$$\frac{b}{2}\left((Z_2)_{out}-(Z_1)_{out}\right)=-\omega U\left(\frac{2a}{b}\sin\frac{\phi_s}{2}\right)\left(\tfrac{1}{2}\rho L^4 M_q'\right)$$

Using these relations the values of the $Z_{\dot{q}}'$, Z_q', $M_{\dot{q}}'$ and M_q' can be obtained, provided that the mass, inertia and metacentric height of the model are known, and that the forces measured during the experiment are split into in-phase and quadrature components. A description of the mechanical detail involved can be found in the publications by Gertler and Goodman[20], although following their lead there are now a number of oscillators in use employing slightly different techniques.

This analysis of pure pitching motion is of interest, because it shows how rotary derivatives can be obtained in the long towing tank. Z_w' and M_w' can, of course, be obtained by the method described previously, but if pure heaving motion is analyzed Z_w' and M_w' can also be obtained using the oscillator. Obviously, with the model on its side the corresponding horizontal plane derivative values can be determined.

This description of experimental methods has been by no means exhaustive, although it has outlined some techniques for obtaining the values of the derivatives required for the simplified equations of motion. An interesting problem not yet resolved is the possibility of their being any difference in the results obtained by direct and indirect methods. It will be of interest to compare rotary derivative values obtained by experiments on the rotating arm, with those obtained by oscillator techniques.

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Retirements

F. H. EDWARDS

Frank Edwards, who retired on the 30th April after nearly 20 years as Superintendent of the Bragg Laboratory, Sheffield, entered the Service in 1936 when he was appointed for duty at the then new Bragg Laboratory. Originally in charge of an outstation engaged in the analysis of ferrous and non-ferrous metals, he later returned to the main Laboratory to take charge of the development of spectrographic methods in the field of metal analysis. A personal contribution to the application of this technique to aluminium alloys resulted in a method for the production of a standard form of test-piece to ensure adequate reproducibility. This method, which was published, was to prove of value in the evaluation of the large volume of samples examined during the war years.

In 1940, he was appointed chemist-in-charge of the CINO laboratory set-up at Birmingham University, which, in addition to the inspection of metal samples, dealt with a wide variety of miscellaneous materials, and also carried out metallurgical investigations which were required by the area INO in an advisory capacity.

At the end of the war, Mr. Edwards returned to Sheffield, firstly to the outstation at the University, and then to the Bragg Laboratory, where in 1949 he succeeded Mr. E. J. Vaughan as Superintendent.

In the post-war years a steady increase in the complexity of alloy development necessitated an increasing sophistication in the methods employed for their analysis, and the Bragg Laboratory under Edwards's direction, contributed to this field of effort in no small measure. The development of methods for Non-Destructive Testing, with special reference to the weapons field, has also been an important facet in the Laboratory's programme. He devoted a great deal of time and effort to service on committees, both MOD(N), Inter-service, Industrial and International, his main sphere of activity being the development and standardization of test methods in the metals, rubber, and plastics fields. In this way he was able to direct the Bragg Laboratory in the pursuance of many programmes of co-operative experimental work.

For the last four months of his Service career, Edwards was seconded to the Directorate of Chemical Inspection, MOD, which has recently assumed responsibility for much of the inspection work carried out for CINO. During the transition period of this re-organization, his long experience as Superintendent of the Bragg Laboratory, and his personal knowledge of the staff involved, proved invaluable in facilitating the re-orientation involved in this operation.

We now wish Mr. and Mrs. Edwards a long and happy retirement in their new home in Seaford, Sussex.

N. I. HENDEY

Norman Ingram Hendey retired on 10th May, 1968, after 28 years' service. Originally qualifying as a Pharmacist, he soon became interested in marine plankton and worked for a number of years in the Department of Botany, British Museum Natural History. He entered Admiralty service in 1940 as an Assistant Civilian Officer attached to the Department of Naval Intelligence. His work with D.N.I. involved much travel, initially taking him to Singapore from whence he made a hasty escape, after which he spent his time commuting between Colombo, Delhi, Ottawa, Canberra, Darwin, Wellington, Honolulu and Guam. During this period he worked closely with the United States Navy, Royal Australian Navy, and the Royal New Zealand Navy.

He returned to the United Kingdom from the South West Pacific in 1945 and joined the staff of the Central Metallurgical Laboratory, Emsworth, to work on microbial aspects of antifouling and the formation of marine slimes. When C.M.L. was closed down in 1956, he joined the Admiralty Materials Laboratory to form a Microbiological Section. This he gradually built up to carry out work on the biodeterioration of a wide range of materials including rubbers, plastics, fabric, wood and oil. His work on finding suitable biocidal agents for the protection of these materials was not only of great value to the Navy, but also had considerable application to civil work, and Norman Hendey was frequently consulted by other Government Departments and firms on their problems.

During his career he retained his interest in marine biology and one of his hobbies was the study of diatoms on which he was an acknowledged world expert. His interest in this field culminated in the publication by H.M. Stationery Office in 1964 of Part V to the series "An Introductory Account of the Smaller Algae of British Coastal Waters" entitled "Bacillariophyceae (Diatoms)"—the only modern standard work on this subject. He was an accomplished lecturer and shortly before his retirement gave the Stredwick Memorial Lecture to the Poole Technical Group on Microbial Attack on Materials. He was active in social affairs and was for many years Chairman of the A.M.L. Social Committee. He took a great interest in local natural history and was Founder President of the Poole and District Natural History Society, which he also represented on the Dorset Naturalists' Trust.

On behalf of his colleagues, Dr. T. C. J. Ovenston presented Mr. Hendey with a copy of the reprint edition of Van Heurek's *Treatise on Diatomaceae* with their best wishes for many happy years of retirement.

C. O. PRINGLE, M.Sc.

Charles Pringle retired on May 24th after 34 years' Admiralty service. He was educated at Methodist College, Belfast and at Queen's University, Belfast where he took his degree in physics and then did research there for his M.Sc. After this he went to Leicester University as a research assistant and later joined the staff at Southampton University. He joined the Signal School, Portsmouth in 1934 and was attached to the Valve Section under H. G. Hughes. He was concerned with the development of silicon transmitting valves which were used as the power sources in all Naval communication sets and which soon after this time were also designed specifically for the radar research then being carried out by Watson Watt at Bawdsey Research Station.

From 1939 Hughes became more and more involved with inter-Service valve matters, and the running of the Signal School Valve Section was left almost entirely to Mr. Pringle. Under him it was evacuated to Waterlooville in 1940 and expanded to include a valve production pilot plant, and also a valve applications and specification group.

He left the valve group at Waterlooville and went to Witley in 1947 as Officer-in-Charge. Among the many administrative duties of this post he was concerned with the planning and layout for the Portsdown Establishment.

In 1948 he moved back to the valve world joining C.V.D., where he was responsible for the financial aspects in the organization. He spent 12 years at C.V.D. covering various duties during the expansion of that organization to its present level.

Mr. Pringle returned to A.S.W.E. in 1962 where he has since worked on various valve problems.

A bachelor, and, rather shy and retiring he has always been very much liked by all his colleagues. In his younger days he was a very active Scouter and still takes a close interest in the Movement, particularly in the Southampton area. More recently he developed a great interest in gardening to which he has applied his scientific talents. He chose to specialize in the more exotic plants, for which he set up an automated environment. With this aid he was able to live in London during the week and still produce show winning plants from his "shed" in Southampton. With the addition of a large walled-in garden he is looking forward to a very active retirement to his special hobby.

H. W. LUFF

Mr. H. W. (Bert) Luff, ex-Senior Draughtsman, retired at the end of March after 47 years in the Service, 30 of which were spent in A.S.W.E. Drawing Office. He started his career as an apprentice in the Electrical Dept. at H.M. Dockyard, Portsmouth, where he specialized in armature winding and repairs. He joined the then Signal School just before the last war and was engaged on the design and drawings of the early radar equipments and subsequently pioneered the Technical Co-ordination Section of the Drawing Office, which brought him into contact with a large number of A.S.W.E. Staff of all disciplines. Mr. Luff was presented with an ornamental porcelain by Mr. A. Lambert, Head of Drawing Office, in the presence of a large gathering of his colleagues.

S. A. HARRIS

After 49 years in the Service, Mr. S. A. Harris, ex-Senior Draughtsman, retired at the end of April. He served an apprenticeship in the E.E.M. Dept., Portsmouth and started in the Signal School Drawing Office in 1931. The majority of his career however was spent on the design of mining equipment in the old Mine Design Department and later at U.C.W.E. As a result of "Way Ahead" in 1959 he was transferred for a short while to A.U.W.E. and in 1960 he completed the circle and returned to A.S.W.E. where he was engaged on monitoring the drawing work being prepared for A.S.W.E. by contractors. Mr. Harris was presented with a cheque by Mr. A. Lambert, Head of Drawing Office, on behalf of the Staff.

Notes and News

Admiralty Compass Observatory

H.M.S. RESOLUTION's Demonstration and Shakedown Operation (DASO) held off Cape Kennedy during the early part of the year, was attended by Mr. J. Crowther, Mr. C. V. Hardy and Mr. E. Hoy. They spent about six weeks at the Cape as members of a team, which also included Naval personnel and contractor's representatives, engaged in heading transfer. This, effectively, was the provision of a precise optical external heading reference for use in the alignment of the Polaris SINS system.

In this particular, the U.K. Weapon System differs significantly from the American one. Encouraging evidence of its success was given by the two missiles following their correct bearings along the Atlantic Missile Range.

Mr. A. F. H. Thomson has joined the Observatory from S.E.R.L.

Mr H. J. Elwertowski, Chief Scientist, visited the United States in March to hold discussions with U.S. Government officials and visit a number of industrial organizations manufacturing navigational equipment.

Mr. Maurice Foley, M.P., Parliamentary Under Secretary, Navy Department, visited A.C.O. during April. Mr. Foley made a tour of workshops and laboratories and subsequently held meetings with representatives of non-industrial and industrial staff groups.

(left to right) *Dr. W. W. Jackson, Mr. H. J. Elwertowski, Mr. Maurice Foley, M.P., Captain T. D. Ross, R.N., Mr M. P. Wooller, Commander A. E. Fanning, R.N., and Mr. I. S. McDonald.*

A successful Anglo-American joint gas bearing group meeting was held at A.C.O. during April. Eleven representatives of an American group, sponsored by the office of Naval Research, met together with a British counterpart group, formed at A.C.O. last year under the auspices of the M.O.D. This event is fully reported on page 237.

Mr. J. Rigby has been elected Mayor of Slough.

The entry of Cupid to the new laboratory block, evidenced by the wedding of Roy Lee and Lyn Piggott, should not pass unnoticed here. All their friends in R and D and beyond wish them every happiness. They deny that the computer upon which they both work arranged the marriage.

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Admiralty Engineering Laboratory

The 3rd Cranfield Fluidics Conference organized by the British Hydromechanics Research Association in conjunction with the Istituto di Tecnologia Meccanica del Politecnico di Torino was held in Turin, Italy on the 8th to 10th May, 1968. Mr. I. P. Pearson of the laboratory together with Mr. J. Leathers of the Plessey Company presented a paper on a "Fluidic Control System for Diesel Generators". This paper was one of 64 papers presented to the conference from 18 countries, some as far afield at Japan, the United States and the U.S.S.R.

Mr. S. J. O. Tinn, head of the Control Section, visited the United States during May. His tour was concerned with "Fluidics" with special reference to the application of gas turbine control, this being one of the laboratory's current interests. Visits were made to various government or government sponsored laboratories and to the Honeywell Controls Laboratories in Minneapolis.

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Admiralty Materials Laboratory

The small Applied Biology Division at A.M.L. has recently been incorporated with the former Rubber and Plastics Division into a new division entitled "Polymers". At the same time, the "Chemistry" Division has been so re-named (from the previous "General Chemistry").

Mr. G. N. S. Farrand visited Canada during May, 1968, to attend meetings of T.T.C.P. Sub-Group P. Working Panel No. 3, and to visit various organizations concerned with the development and application of polymeric materials.

Mr. D. A. Fanner visited the U.S. during May, 1968, to attend the Power Sources Conference at Atlantic City and to visit U.S. Government agencies and their contractors to discuss work in progress on fuel cell development.

Mr. D. Birchon presided at the opening session of the First Symposium organized by the newly formed Materials Panel of the Institute of Marine Engineers on the subject of "Corrosion in Seawater Services". He has also presented the following papers:—

"The Use of Hidomets in Engineering" at Loughborough University of Technology—January, 1968; "Metallurgy and Non-Destructive Testing" at Cardiff University—February, 1968; "A New Look at Non-Destructive Testing" at the National Non-Destructive Testing Centre, Harwell—March, 1968; "The Metallurgist's Contribution to Economy in Design" at the Conference on "Materials—Properties and Applications" sponsored by the Production Engineering Research Association, Melton Mowbray—March, 1968; "Modern Engineering Materials" at a meeting of the Portsmouth and District Chemical Society.

Dr. D. J. Godfrey presented a paper entitled "The Use of Ceramics in High Temperature Engineering" at a course sponsored by the Metals and Metallurgy Trust, Nottingham—April, 1968.

Admiralty Underwater Weapons Establishment

Co-operation in the development of an underwater towed vehicle for use in oceanographic research was discussed by members of the Natural Environment Research Council during their recent visit to the Admiralty Underwater Weapons Establishment at Portland. The A.U.W.E. is currently working on the dynamics of underwater towed vehicles and their experience will be valuable in future design of vehicles for research purposes.

The visitors saw the first version of an underwater towed vehicle which has already completed trials in a wind tunnel and in the ship tank at the National Physical Laboratory, Feltham. A fully controllable version of the vehicle will undergo sea trials later this year. Although at first restricted to depths of about 80 metres and speeds of 10 knots, later developments are expected to extend these limits. The body will be capable of carrying a variety of instruments, and data collected will be transmitted to the towing vessel by means of electrical connections in the towing cable. Dr. J. E. Wood is in general charge of this work.

Mr. D. J. Maclean, the Deputy Secretary (Scientific) of the N.E.R.C., said that an underwater towed vehicle promised to be a useful tool in oceanographic research and in the new and exciting world of underwater exploration. He said that the Oceanographic Laboratory of the Scottish Marine Biological Association (Director Mr. R. S. Glover), was currently concerned with the development of an oceanographic research device suitable for towing behind merchant ships and able to monitor some of the physical characteristics of the ocean between 10 and 100 metres in depth whilst collecting samples of the plankton.

It is with pride that we report that Mr. Hugh McGrath, Artificer at A.U.W.E. Portland has been elected Mayor of the ancient Borough of Weymouth and Melcombe Regis from May 1968. Mr. McGrath is aged 51 and was born in Glasgow. He served his apprenticeship in marine engineering at Alexander Stephens, Linthouse, Glasgow.

In 1945 Mr. McGrath joined Admiralty Service at the Anti-Submarine Experimental Establishment at Fairlie, Ayrshire, as a Laboratory Mechanic and transferred to Portland in 1946 when the Establishment returned to Portland after war-time evacuation. He was promoted to Technical Grade III in 1964.

For some 25 years he has been active in trades Union matters, holding office as chairman and secretary of Whitley Council; he was also a shop steward for several years.

Mr. McGrath has been a member of the Weymouth Town Council for some 14 years; Chairman of the Harbour and Industry Committee for six years during which time Weymouth became the main port for British Rail steamers to the Channel Islands.

During Mr. McGrath's service on the Council one Industrial Estate has been completed and occupied and another one set up.

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Services Electronics Research Laboratory

Mr. A. F. H. Thomson left on the 25th March, 1968, to take up duties at A.C.O. Slough. At a party given in his honour, at the Sun Hotel, Hitchin, he was presented with a multi-range test meter, as a parting gift from the staff at S.E.R.L.

Mr. J. W. Allen was invited by C.E.R.N. in Switzerland to give two talks on 2nd April, on display, imaging and other semiconductor devices.

Mr. J. Pollard led the British Delegation to the International Standards Organisation Working Group on Vacuum Gauge Calibration, which met in London on

24th and 25th April, 1968. Delegates were present from Belgium, France, Germany, Holland and U.S.A. with observers from the U.S.S.R.

Messrs. R. Redstone, C. H. Gooch and M. Hillier visited Canada in May to attend the meetings of Working Group J.10 of T.T.C.P. at Quebec. Mr. Gooch also made other visits to Canada and the United States. Mr. Hillier and Mr. M. S. Wills attended the Quantum Electronics Conference at Miami, Florida and afterwards visited laboratories in the U.S.A. doing research and development on lasers.

About 65 people from leading British firms attended a symposium at S.E.R.L. on Potentialities of High-Power Carbon Dioxide Lasers in Industrial Processes on Wednesday 1st May, 1968. The symposium was organized by Mr. M. Hillier.

Tam Dalyell, M.P. for West Lothian, who is a member of the Select Committee on Science and Technology, recently visited S.E.R.L. in a private capacity as an M.P., and toured the Laboratory.

left to right: *Mr. P. Gurnell, Dr. H. A. H. Boot, Mr. C. P. Wright, Tam Dalyell, M.P., Mr. P. D. Lomer, Mr. C. P. Lea-Wilson and Mr. R. Redstone.*

First All Gas Turbine Warship Starts Trials

The world's first major warship to be propelled entirely by gas turbine engines, H.M.S. EXMOUTH has now completed trials.

H.M.S. EXMOUTH, which was converted and refitted at H.M. Dockyard, Chatham, has a Rolls Royce *Olympus* engine for full power and two Rolls Royce *Proteus* engines for cruising. Both these are marinized versions of well-proved and reliable engines used in a variety of commercial applications.

The Royal Navy has pioneered the use of gas turbines in warships for over 20 years, and the knowledge and experience gained led to the use of the *Proteus* engine in the *Brave* Class of Fast Patrol Boats, and to the combined steam and gas turbine plants in the *Tribal* Class frigates and the *County* Class guided missile destroyers.

The Royal Navy intends using combinations of gas turbine machinery modules for all future major warships, and by getting the *Olympus* engine to sea as a main propulsion unit in H.M.S. EXMOUTH, will gain further valuable knowledge of the operational characteristics and benefits of gas turbine engines, in the rigours of naval service.

The gas turbine installations in the EXMOUTH can be remotely controlled from the bridge, and benefits include significant reduction in space and weight; the possibility of a main engine change in 48 hours; simplicity of installation, and savings of up to 25 per cent in valuable technical manpower.

Other new features include the use of gas turbine for driving the main electricity generator, incorporating a waste heat boiler to produce steam for auxilliary and domestic purposes. A controllable pitch propeller is fitted for astern operations.

New Surface-to-Air-Missile for the Navy

The PX 430, the close range surface-to-air guided missile which was announced in February by the Minister of Defence (Equipment) as the next generation *SEACAT* missile for the Royal Navy, is to be known as the *SEAWOLF*.

SEAWOLF is designed to give ships a greatly improved self-defence capability against supersonic anti-ship missiles and aircraft in the 1970s. It will be an all-weather system. It is also being designed for use against ships and hovercraft.

POTENTIALITIES OF HIGH POWER CARBON DIOXIDE LASERS IN INDUSTRIAL PROCESSES

The Services Electronics Research Laboratory at Baldock, Herts, held a one day symposium on 1st May to disseminate information on the industrial applications of high power carbon dioxide lasers. This type of laser, invented only three years ago, emits at a wavelength of 10.6 microns—20 times the wavelength of visible light—and is the most powerful and efficient terrestrial source of continuous radiation; as such it is likely to be widely applied as a heat source. S.E.R.L. has conducted molecular laser research and development in its role as a Ministry of Defence Establishment and was the first laboratory to demonstrate laser action from a molecular gas in 1963. The industrial potentialities of this type of laser became apparent early in the programme and special efforts have been made to ensure that the facilities and results obtained are available to industry. In the last 18 months, over 100 firms have consulted S.E.R.L. about possible applications many of which have been assessed in the Laboratory. At the same time, in consultation with Mintech and the manufacturers, results of laser development have been made available and high power lasers are now being made under licence in industry.

The symposium was organised to bring together companies interested in applying these lasers to industrial processes, with laser manufacturers and developers. The majority of the 80 participants was from potential user industries with representatives of supply manufacturers, universities, nationalised industries, Mintech and Ministry of Defence.

Output powers of several kilowatts at efficiencies up to 20%—very high for lasers—have been achieved from carbon dioxide systems. In an opening paper, A. Crocker of S.E.R.L. described the present status and development trends. Conventional carbon dioxide lasers can be made more powerful simply by making them longer; powers of 7 kW have been reported from tubes up to 600 ft long. Such experimental lasers are too bulky for industrial processes even though a folded, zig-zag construction can be rather expensively introduced. Ways must be found to reduce package size. Experiments have shown that the glass laser tube diameter cannot usefully be changed from a few centimeters. A mixture of helium, nitrogen and carbon dioxide is used and this must be flowed through the system at a rate which will give about two system changes per second. It is essential to maintain a low gas temperature and the heat dissipated in the laser must be removed by conduction to the tube walls, a process which is more efficient in small diameter tubes. S.E.R.L. has tackled this problem in two novel ways to incorporate the advantages of small diameter tubes in compact high power devices.

The first approach is to mount small diameter lasers in parallel and to combine the separate output beams optically to give a high intensity focused spot. Powers of over 75 W/metre length are being achieved with single tube lasers and three such tubes were combined in an experimental version on display. A bank of tubes housed in a container 10 cms diameter and 3 m long should be capable of one kilowatt output.

A more advanced approach, demonstrated for the first time at the symposium, is an annular tube laser. The electrical discharge occurs in the annular region with cooling of both inside and outside walls. Powers up to 210 W/m from a 5 cm diameter annulus have so far been obtained during development for this device—a factor of three times the performance from a comparable cylindrical tube.

In a paper on the utilization of 10.6 micron radiation, M. Hillier of S.E.R.L. highlighted the effects of laser design and infra-red optical component quality on the focused diameter. The highest intensity—smallest focus—is achieved with a single mode laser, that is, one with a singly peaked distribution of power across the beam diameter. Theoretically, intensities of over 100 MW/cm^2 are possible; in practice, tens of megawatts per square centimeter have been realised with spot diameters of about 25 microns. Single mode operation produces less total power than multimode operation, commonly by a factor of about four. Multimode lasers are also more stable, cheaper and commercially available so that where minimum spot size and/or maximum power is not required, they are an economic choice. Power densities up to several megawatts/cm^2 in a 100 diameter spot should be obtained from a 500 watt laser.

TABLE I. CO_2 Laser Cutting 500 W, 4 MW/sq.cm.

Material	*Thickness inches*	*Rate Ft/min*	
Synthetic Rubber	0.1	30	
Wood (Pine)	0.75	6	
Paper	0.015	1,000	
Quartz	0.040	20	
Fabric: Nylon	3 oz	>250	Limited by apparatus not laser
Terylene	8 oz	>250	
Cotton	8 oz	>250	

Comparative cutting rates for a range of materials are shown in Table I. These are based on experimental data obtained at S.E.R.L., normalized to a 500 watt laser with a power density at the focus of 4 MW/cm^2. Table II gives comparative welding rates with a laser of the same power output.

TABLE II. CO_2 Laser Welding 500 W

Material	*Thickness inches*	*Rate Ft/min*	*Weld Type*
Polythene / Polypropylene	0.005	>160	Edge
Stainless Steel	0.005	30	Edge
Nimonic 90	0.011	> 5	Butt
Titanium	0.018	> 3	Butt
Tantalum	0·005	> 3	Butt

Notes: Thickness quoted are per sheet.
Focus adjusted for optimum weld.
Rates quoted were limited by transverse speeds not lasers (except stainless steel).

Metal cutting by the oxygen-assisted laser process was described by P. T. Houldcroft of The Welding Institute who also discussed in detail the recent work carried out by members of the Institute using the S.E.R.L. 250 W laser. High speed colour photography of the cutting action has shown that the 100 p.p.s. radiation from the a.c. excited laser initiates the formation of a cone of molten metal and oxides whose temperature is maintained during its ejection by the oxygen jet. Although the laser radiation raised the surface metal to a temperature much higher than that required for burning by exothermic reaction with oxygen, the film showed that the reaction was sustained only for a very short time after the cessation of the light energy pulse. A continuous laser has been developed by S.E.R.L. for The Welding Institute for further studies of metal cuttings. The role of the carbon dioxide laser in metal cutting was discussed by B. F. Scott of Birmingham University.

After a tour of the laser laboratories at S.E.R.L. a discussion was introduced by Mr. Lunau of The British Oxygen Co., who felt that the Symposium had gone a long way to promoting knowledge of the carbon dioxide laser and its industrial potentialities.

NOTICE TO READERS

The Editor extends to all readers of the JOURNAL a cordial invitation to contribute articles of R.N.S.S., Naval or general scientific and technical interest.

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